Paper Number

Targeting the Limits of Laser Doppler Vibrometry

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ABSTRACT

Laser Doppler Vibrometry (LDV) is the workhorse for hard disk drive dynamic testing and has contributed significantly to the development of modern hard disk drives. With increasing areal densities, and component as well as drive miniaturization the performance requirements for laser Doppler vibrometers (LDVs) have continuously grown to confront the demands of increased resolution, bandwidth and accuracy. In this paper we address the limitations of LDV technology and how to get close to those limits. Conventional analog signal processing schemes and modern digital decoding methods are discussed. Examples are given for LDV measurements requiring high resolution digital signal processing and high frequency capability of analog demodulation.

INTRODUCTION

One of the first references to LDV design was Drain's 1975 book "The Laser Doppler Technique" [1]. Subsequently LDVs have become a indispensable tool for the accurate measurement of vibration on small and miniature structures. From these measurements, natural frequencies and mode shapes are extracted and modal parameters like modal mass, stiffness and damping calculated. In early days, LDV measurements were mainly applied to larger structures such as automotive components. Original LDV designs were solely based on bulk optical components. In 1985 [2] and 1988 [2] Lewin presented an improved design incorporating fiber optic light guides. Within a very short time fiber optic based LDVs became the standard tool in the data storage industry and found many different applications in R&D as well as production testing.

MAIN SECTION

Laser Doppler Vibrometer Principle of Operation

The Laser Doppler Vibrometer (LDV) is a non-contact velocity and/or displacement transducer, which is used to measure magnitude and frequency content of large, down to micron size parts. LDVs focus a laser beam on the structure to be tested. The structure scatters or reflects light from the laser beam and the Doppler frequency shift or phase shift of the backscattered light is demodulated to measure the component of velocity / displacement, which lies parallel to the axis of this laser beam.

Because of their non-contact nature, LDVs do not mass-load the structure which is a prerequisite for data storage components, furthermore the natural stiffness and damping of the component is not changed. Laser Vibrometry is a very sensitive optical technique capable of measuring sub-nanometer or even sub-picometer displacements from near DC to several MHz. In addition to their wide frequency range, LDVs have dynamic range not matched by other sensors. This enables measurements that cannot be accomplished by other optical techniques.

The Laser Doppler Technique
Optical Arrangement

For measurements on data storage drives, MEMS and other small structures the low noise level and high resolution of the LDV are of utmost importance in order to detect the smallest vibration levels. In addition to the noise created by signal demodulation electronics, phase noise of the laser contributes to the overall noise of an LDV system. The phase noise corresponds to the line width of the light source.

The low noise of a single mode HeNe laser, with narrow line widths of in the order of a few millihertz, make it the preferred light source for LDVs.

In general, two different optical arrangements for LDV's have been popular**:** the homodyne and the heterodyne vibrometer techniques. In a homodyne vibrometer the vibration direction is obtained by processing 2 interference signals (I & Q) which are shifted 90° versus each other. Due to certain disadvantages of the homodyne technique, most commercially available LDVs are now using the superior heterodyne technique. In this the frequency of a reference beam is shifted by an acousto-optic modulator or Bragg cell.

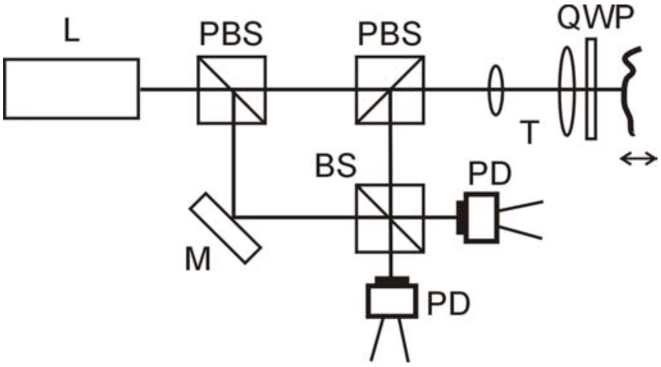

Figure 1: *Optical arrangements of the classical Mach-Zehnder type interferometer. M is a mirror, BS is a beamsplitter, PBS is a polarizing beamsplitter, L is a laser, QWP is a quarter-wave plate, PD is a photo detector, and T is a telescopic lens array.*

In the Mach-Zehnder interferometer, as shown in figure 1, the laser beam is divided into 2 beams (measurement and reference beams) utilizing a polarizing beam splitter. A quarter-wave plate rotates the polarization of the back-reflected light by the test object by 90° and another beam splitter guides it to the detector. Here the measurement beam and the reference beam are combined. Two photo detectors are used to receive twice the signal power and to remove the DC component.

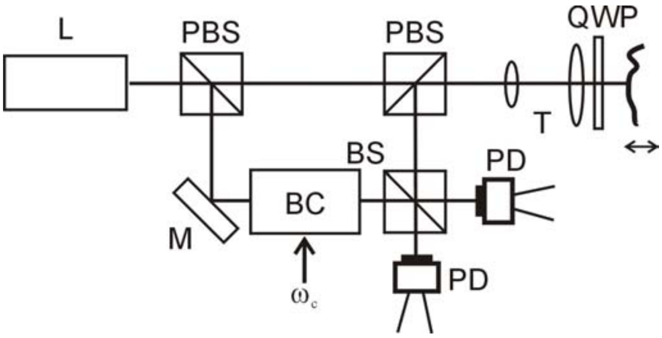

Figure 2*: Schematic of the optical arrangement of a heterodyne vibrometer. BC is a Bragg cell*

In the heterodyne interferometer as shown in figure 2, an acousto-optic modulator, BC, is incorporated for frequency shifting of the reference beam. The most common shift frequencies are 40MHz and 70MHz.
Without any motion (v_{object}=0) the photo detector will see only the Bragg cell reference frequency ω_c With v_{object} >0 the photo detectors will detect either an increase or decrease in frequency depending on the motion direction of the object.

Resolution Limits of Laser Doppler Vibrometry

Resolution is a crucial parameter when applying LDVs to data storage component measurements. The main noise sources limiting the LDV resolution are light induced noise (shot noise), thermal noise of detector and preamplifier (Johnson noise), and signal processing noise. The ultimate limiting factor of a LDV is the signal-to-noise ratio of the photo detector output.

An exact calculation of the LDV resolution is very complex and would extend the scope of this paper. Hence only some basic relationships are given hereafter. A major advantage of coherent light detection by means of an interferometer is the optical amplification of the AC amplitude which can be expressed by the term

$$\sqrt{P_m P_r}$$

P_m -Measurement beam power, P_r - Reference beam power

This means doubling the power of the reference beam yields a •2 or 3dB gain for the carrier amplitude (=optical amplification). However the sum power $P_m + P_Y$ not only generates a DC current, but also shot noise:

$$\bar{i}_{sh}^2 = 2K \cdot q \cdot B(P_m + P_r)$$

B – detector bandwidth
K – detector sensitivity factor (A/W)
q – electron charge

Another noise source is thermal noise of the detector/preamplifier combination:

$$\bar{i}_{th}^2 = \frac{4k \cdot T \cdot B}{R}$$

k – Boltzmann´s constant
T – absolute temperature
R – detector load resistance

The reference beam power is usually chosen such that shot-noise power significantly exceeds thermal noise power under given conditions. This point is usually reached at $P_r + P_m$ < 1 mW, depending on bandwidth. The system then is called shot-noise limited and yields the best possible signal-to-noise ratio.

As shown before, with an appropriate interferometer design, shot noise provides the main contribution to the detector output noise.

An LDV system provides displacement information by decoding the phase shift and velocity from the frequency shift (Doppler shift). When looking at the characteristics of the overall noise; it can be shown that phase noise (equivalent to displacement noise) exhibits white noise characteristics, whereas the velocity (FM) noise is proportional to the frequency. This is the reason why velocity noise increases at higher frequency, whereas the displacement noise is constant over frequency.

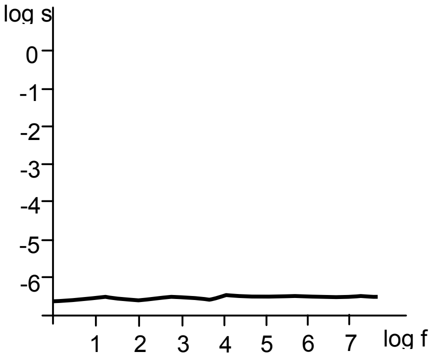

Figure 3: *Spectral distribution of displacement noise*

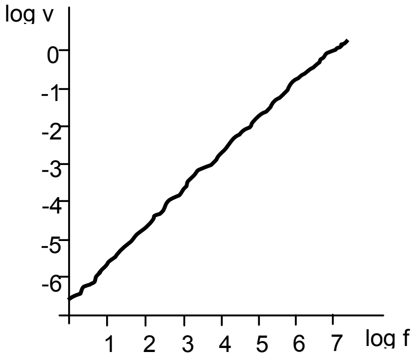

Figure 4: *Spectral distribution of velocity noise*

We have calculated the theoretical noise-limited resolution for an interferometer powered by a 2mW HeNe laser assuming a split ratio of 50:50 for reference and measurement beams, a quantum efficiency η=0.8 and an efficiency factor ε=0.8 for an object with a reflectivity of 10%.

We obtain a mean square displacement noise-equivalent of 4 femtometers per square root Hz.

In real LDV's, additional broad-band noise as well as spurious noise components are present, pushing the practical resolution to higher numbers. Under conditions comparable to the above example, a displacement noise floor of less than 50 fm/•Hz is achieved with a commercially available class II laser vibrometer (1 mW output) in combination with digital decoding. Spurious noise peaks, caused mainly by electronic crosstalk, are not higher than 25 pm.

The corresponding velocity noise of this system rises from <0.5 nm·s^{-1}/√Hz to 0.3 µm·s^{-1}/√Hz in the frequency range of 0 – 2 MHz.

Sub-picometer resolution is achieved under the condition of sufficiently small resolution bandwidth of the subsequent signal acquisition system or using an adequate number of averages. This is usually not a problem when analysing stationary vibrations or repetitive dynamic processes. For analysis of transient processes, however, the so-called single-shot resolution is crucial. The acquisition bandwidth depends on time rise requirements and it is in the order of tens of kilohertz or even megahertz. The resulting measurement resolution is calculated for a given bandwidth B according to $\bar{s} = \bar{s}'\sqrt{B}$. On account of the stochastic nature of noise, one should multiply this value by a factor of five in order to get an estimation for peak-to-peak noise in a single-shot acquisition.

Laser Doppler Signal Demodulation

Before discussing different ways of decoding the Doppler signal lets have a closer look at the properties of that signal:

The phase modulated signal exhibits a linear relationship between phase *$\varphi(t)$* and object displacement *s(t)*:

$$\varphi(t) = \frac{4\pi \cdot s(t)}{\lambda}$$

A phase modulation generates a frequency modulation f_D at the same time which is determined by the velocity of the object *v* and the vibration frequency f_{vib}:

$$\Delta f_D(t) = \frac{2\hat{v}}{\lambda}\cos\left(2\pi f_{vib} t + \phi_s\right)$$

The bandwidth of the frequency modulated signal can be calculated by the simple term $BW_{het} = 2(\Delta f + f_{vib})$

Hence the bandwidth depends not only on the vibration velocity but on the vibration frequency as well which becomes important when making measurements in the MHz regime. The frequency of the acousto-optical modulator (Bragg cell) must be at least $\Delta f + f_{vib}$ With the common Bragg cell frequency of 40MHz velocities up to 10m/s (equivalent to Δf=±32MHz for a HeNe laser) can be handled. For smaller velocities the maximum vibration frequency f_{vib} can be as high as 30MHz.

In order to process signals of up to 10m/s in velocity or up to 30MHz in vibration frequency, from the above relationships follows that an LDV with 40MHz Bragg cell signal demodulator ideally would handle a bandwidth of at least ±32MHz. At the same time there is the request for highest resolution at small velocities. We will see next that different decoding schemes are needed for meeting both requirements.

Laser Doppler Signal Processing utilizing Analog Techniques

Analog Velocity Decoding: Commercially available LDVs are using analog frequency demodulation for converting the Doppler frequency into an analogue voltage proportional to the velocity of vibration. There are many different principles for demodulation; ranging from plain single chip FM decoders to more sophisticated delay-line techniques.
The basic principle of most analog velocity decoders is shown below. The frequency to voltage converter should exhibit high linearity and the adjustable scaling amplifier is responsible for an accurate calibration factor.

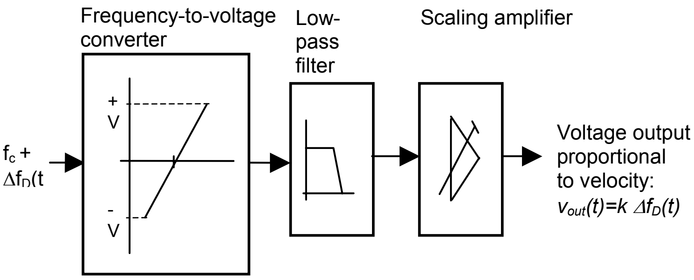

Figure 5: *Principle processing chain of an analog velocity demodulator*

Analog velocity decoders can be matched to a variety of processing requirements such as very high frequency, DC response and high velocity ranging. These are still the preferred choices when it comes to measurements at high speeds (10m/s or more) and high frequencies. However, one must have in mind that analog electronics are sensitive to drift as well as aging, and there are certain limits in linearity and those must be calibrated for accurate measurements.

Analog Displacement Decoding: Analog displacement (or phase) decoders are used for measurements of ultrasonic vibration up to 30MHz. Such decoders utilizing PLL circuits detect the phase of the signal in a range of ±90 degrees and are therefore limited to relatively small displacements (±λ/8 or about 150nm peak to peak for HeNe Laser).
The most popular method for achieving displacement information is an analog integration of the velocity signal. However such analog integrators always require a high pass filtering of the velocity signal. Thus DC measurements are not possible, but are limited in their dynamical range and additional errors are added to the calibration chain of the system.

Laser Doppler Signal Processing Using Digital Techniques

The only way to overcome the limitations of analog processing is to digitize the LDV signal and use numerical methods for the demodulation. High speed DSPs are used for achieving nearly real-time decoding, whereas high bandwidth ADCs are needed for dealing with the large bandwidth of the Doppler signal.
With DSP based LDVs significant improvements in resolution can be achieved under certain conditions.

This is an important progress for using LDVs in the development of modern HDD drives and components. Without any doubt DSP technique will play an important role in the future of LDV innovations although for certain measurement conditions (high velocity / high frequency) analog demodulation is still needed.

The classical method of Digital Displacement (DD) decoding is the so-called fringe counting method which is used by many available LDVs: A simple digital counter measures the zero crossings of the interference fringes passing the photo detector. A complete period or 2π phase increment is equivalent to a displacement of λ/2 (316nm for HeNe laser). For low velocities and low vibration frequencies the resolution can be increased to 2 nm per count by so-called phase multiplication techniques.
Although fringe counting has been used for many outdated data storage applications such as end-stop measurements with low areal densities, the resolution and frequency limits are no longer adequate for modern drive developments on which ramp-load-unload has replaced media landing zones for read-write heads.

Fringe-counting measures the phase in discrete increments of 2π or its submultiples. A continuous phase measurement should result in a much higher displacement resolution.

Arctangent phase demodulation is such a method for continuous phase measurements. A prerequisite for this method is a quadrature I & Q signal pair without any frequency offset:

$$u_i(t) = U_i \cos\varphi(t)$$

$$u_q(t) = U_q \sin\varphi(t)$$

Each of the signals contains the displacement information whereas the combination of the 2 signals yields the direction of motion.
The I&Q signal pair can be created numerically after digitization of the Doppler signal or by a so-called analog quadrature demodulator:

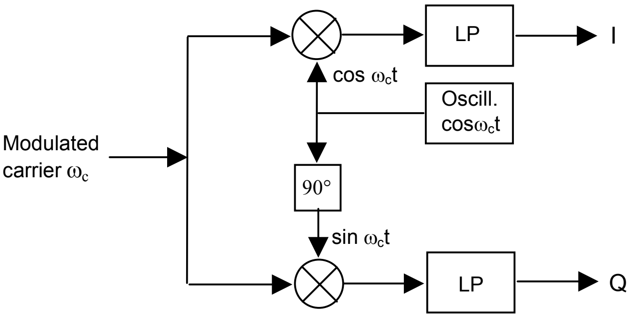

Figure 6: *Principle for generating an I&Q quadrature signal from a modulated carrier*

This circuit converts the frequency shifted Doppler signal into an I & Q base band signal with 90 degrees shift versus each other. The I & Q signals are digitized by a pair of appropriate A/D converters. As both signals are in the base band with the frequency offset (typically 40MHz) already removed the performance requirements for the A/D circuit are much lower than for a direct digitization of the heterodyne Doppler signal.

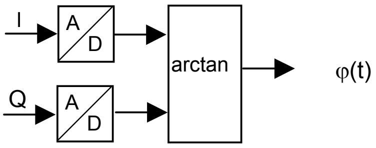

Figure 7: *Processing chain of the I&Q signals*

The phase angle calculated from the digitized I&Q signal pair

$$\varphi(t_n) = \arctan\frac{u_q(t_n)}{u_i(t_n)} + m\pi \ , \quad \text{m = 0, 1, 2, ...}$$

is directly related to the displacement of the object

$$s(t_n) = \frac{\lambda}{4\pi}\varphi(t_n)$$

Hence by calculating the phase angle a displacement measurement with very high resolution can be achieved.

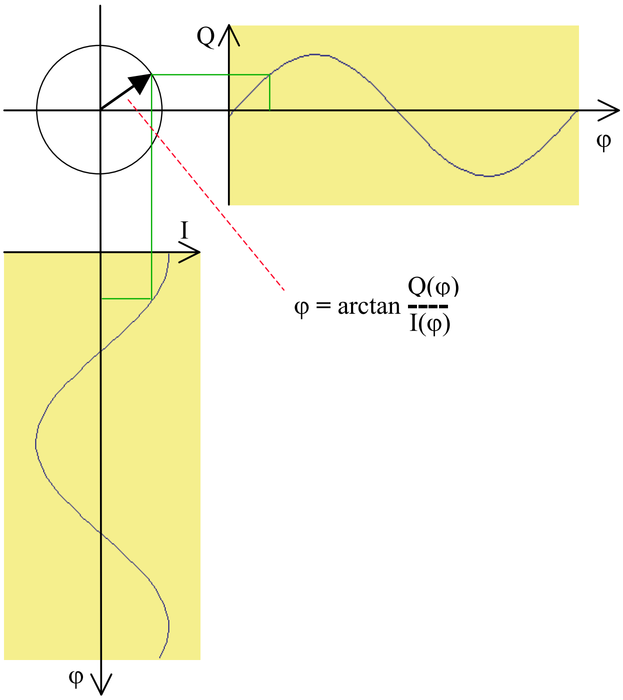

Figure 8*: The I & Q signals can be described as a rotating vector in a vector diagram. Ideally this vector describes a perfect circle.*

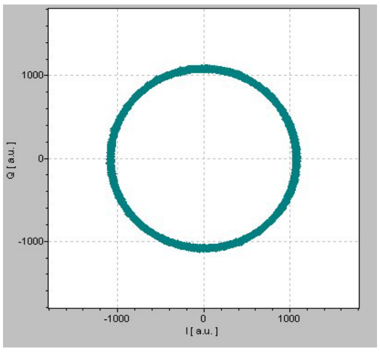

Figure 9: *Visualization of the I&Q vector for vibration levels s > λ/2*

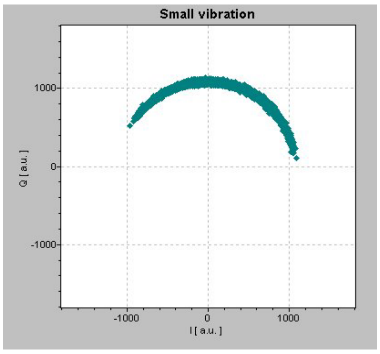

Figure 10: *And for small vibration levels s < λ/2*

An arctangent LDV system has been realized on PC platform. The detector signal is converted into the I&Q pair using an analog quadrature demodulator as shown in figure 6. Next, the I&Q signals (plus one reference signal) are digitized by an of-the-shelf A/D board and the signal phase is numerically calculated (figure 7). This system has already been extensively used for measurements on data storage and MEMS components. Not only for measurements on single points but also in conjunction with microscope scanning vibrometer (MSV) systems for full area mapping through a microscope and with dual beam MSV systems for differential measurements. With sufficient number of averages a resolution of less than 1 pm has been achieved bringing us closer to the resolution limit of LDVs as discussed beforehand.

A/D Sampling Freq.	5.12 Msa/s
Max. vibration freq.	2 MHz
Max vibration velocity	810 mm/s
Specified displacement resolution	<1 pm per sqrt Hz
Specified velocity resolution	<0.1 µm/s per sqrt Hz

Table 1: *Specifications of a PC platform based laser Doppler vibrometer*

Further improvements in vibration velocity and frequency can be achieved by higher sampling rate ADCs and are foreseen as a next development step.

Laser Doppler Signal Processing utilizing Digital and quasi Real-Time Techniques

The LDV concept described before utilizes a PC platform for digitalization of the I&Q signal pair and processing of the phase. Hence a proprietary PC software for data processing and display is always needed and an analog real-time output is not available. Consequently the next development step would be implementing this concept onto a real-time DSP platform without any need for PC hardware.

In the arctangent DSP-based LDV the Doppler signal is down mixed to a lower intermediate frequency and digitized by an on-board A/D converter. The I&Q signal pair is created numerically by mixing the signal with a numerical oscillator (NCO). The arctangent calculation provides the phase of the signal. To save calculation time and DSP power the phase is not unwrapped but differentiated in order to achieve velocity values. The velocity data are converted into an analog voltage using a 16 bit D/A converter.

The entire signal processing shown in figure 11 (upper part) has been integrated onto a single board.

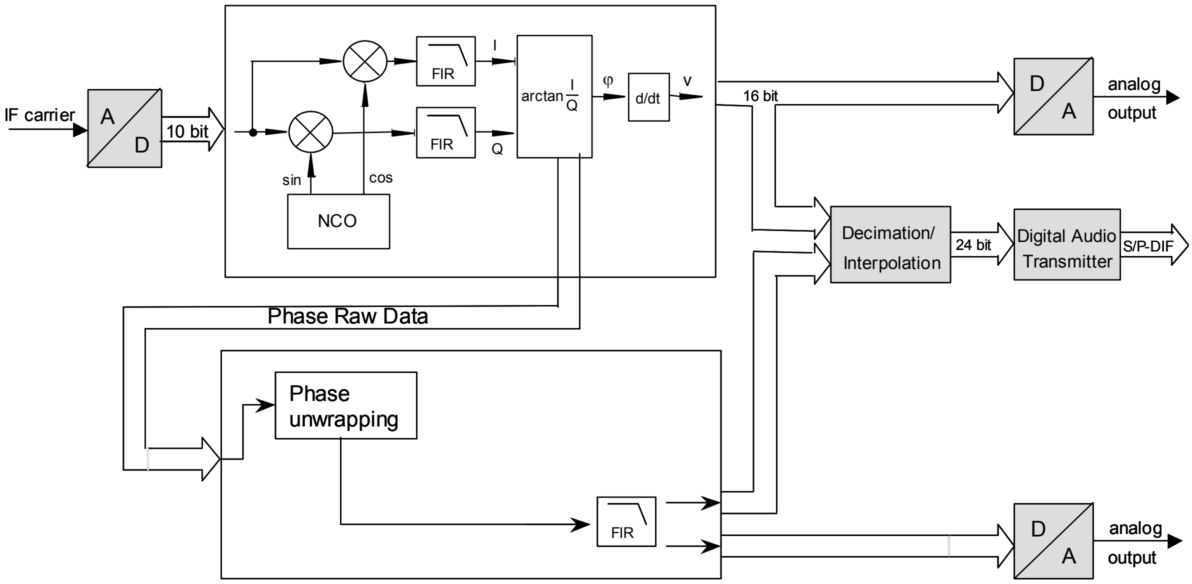

Figure 11: *Block diagram of a quasi real-time DSP based decoder for velocity and displacement*

A propagation delay of about 10us is achieved with a 50MHz DSP which is about 3 to 4 times slower than an analog demodulator. This longer propagation delay must be considered when doing phase measurements. However, the delay is frequency independent and perfectly constant. The phase response is extremely linear over the entire frequency range and may be compensated in the data acquisition systems software. In terms of resolution and signal to noise, the described digital decoder is superior to analog techniques, due to the absence of certain noise sources. The displacement resolution calculated from the velocity values has been found to be as low as 0.1pm/√Hz under ideal conditions.

Max. vibration frequency	350 kHz
Max. vibration velocity	500 mm/s
Number of velocity ranges	configurable
Velocity resolution	0.02 µm/s per sqrt Hz

Table 2: *Specifications of a DSP based arctangent velocity decoder*

The original phase information is immediately differentiated to achieve velocity data. Using an additional DSP circuit, phase unwrapping can be performed in real-time resulting in a synchronous output of displacement in addition to the velocity data (figure 11, lower part).

The resolution of the displacement data is limited by the D/A conversion to 15pm per bit. This is not as good as for the PC based arctangent demodulation which can achieve less than 1 pm resolution. However it is a huge improvement compared to the conventional fringe counter technique which is limited to 2nm and to relatively low frequencies. In particular for data storage applications, we think that this new quasi real-time and high resolution displacement decoder technique will replace conventional “fringe counters” or analog integrator techniques.

Max. vibration freq.	350 kHz
Max vibration velocity	500 mm/s
Number of displacement ranges	15 (1-2-5 steps)
Displacement resolution	15 pm (DAC resolution) 0.5 pm /√Hz noise-limited spectral resolution

Table 3: *Specifications of a DSP-based displacement decoder*

Applications for a New Generation of Laser Doppler Vibrometers

There are many different applications for LDV techniques in the development and dynamic testing of modern data storage drives and components such as

- Head/media interface dynamics
- Head load/unload dynamics
- Track seek and track dynamics stability
- Component resonance testing for voice coil, actuator arm, suspension
- Drive level resonance testing
- Component and system modal analysis
- Spindle testing, RRO und NRRO measurements
- Media testing

Some of these applications have very different requirements for the LDV system in terms of resolution and frequency. Hence the only way to cover all of these applications with a single LDV is by combining different decoder techniques in one single instrument. We are using up to 4 decoders simultaneously utilizing analog and digital, velocity and displacement demodulation.

In the application part of this paper we want to address 2 such applications: Head resonance testing of high frequency modes requiring the highest possible resolution. And testing of HDD media requiring very high frequencies for resolving smallest details on the media surface.

LDV investigation of Low Amplitude Sensitivity Air Bearing Resonance Modes During Vacuum Pumpdown

As disk drives become ubiquitous storage devices in automotive, home appliances (TiVo) and in recreational (iPod) applications, they are subject to increased environmental conditions. One of those is changes in atmospheric pressure. These changes induce gradient in the flying height (FH) and general flyability and dynamics of the air bearing interface between media and slider. Hitachi Global Storage Technology (HGST) in San Jose California is a leading center of in his field. Feliss et. al. have worked extensively in methodologies to simulate the effects of high-altitude on HDDs to study the air bearing modes changes [6].

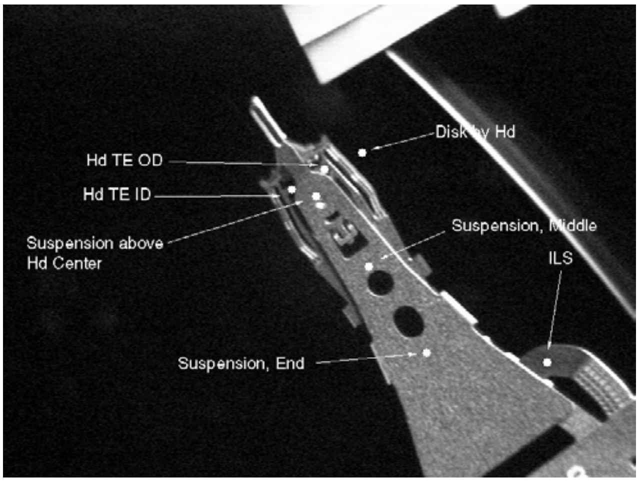

Figure 12: *Suspension and parts under study.*

Depending on those dynamic changes, heads with centered pivots or with forward pivots will require different specially built suspensions. It is ideal to find the right combination of slider pivot point location and suspension design. Furthermore, if an unsuitable combination is chosen resonances may transfer through the suspension and the other heads on the head-stack assembly. Figure 12 shows one of the HGAs (head gimbal assemblies) under study. Figure 13 shows a Polytec Scanning Vibrometer (PSV) measuring a drive or file in the vacuum chamber

Figure 13*: PSV measuring file in vacuum chamber*

Figure 14 shows the laser beam of a Micro Scanning Vibrometer (MSV) measuring a location on the trailing edge (TE) of the slider. Measurements were done for two configurations; one with the center pivot point compared with the forward pivot point (see figure 15).

Figure 14. Laser beam of an MSV measuring a location on the slider TE

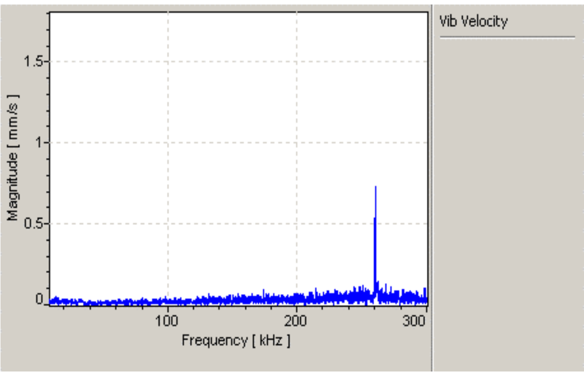

Figure 15: *FFT HD ID corner on forward pivot drive @ 0.90 atm MAG = 0.75 mm/s at 263kHz*

The drive with centered pivot (Fig. 16) compared to the drive with forward pivot (Fig. 16) does not exhibit a large 263Hz peak on the slider trailing edge or suspension.

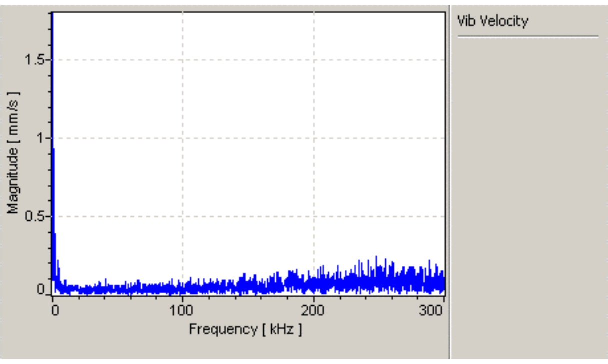

Figure 16: *FFT HD ID corner @ 0.90 atm on TE with drive with center pivot*

As the atmospheric pressure decreases the altitude also decreased, the drive with forward pivot makes contact with track 1000 at 0.540 atm. Roll and bending modes of the air bearing enter in resonance at this condition.

These events are shown clearly in figures 17 and 18.

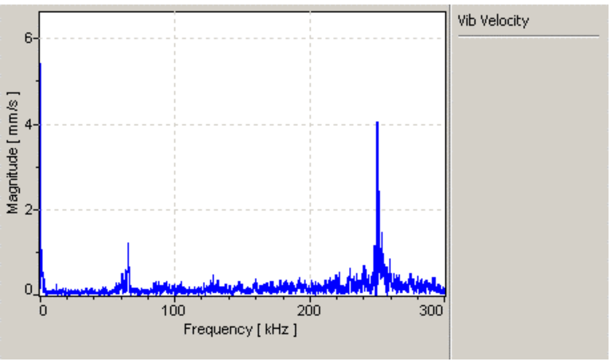

Figure 17: *FFT HD ID corner @ 0.560 atm on TE with drive with forward pivot*

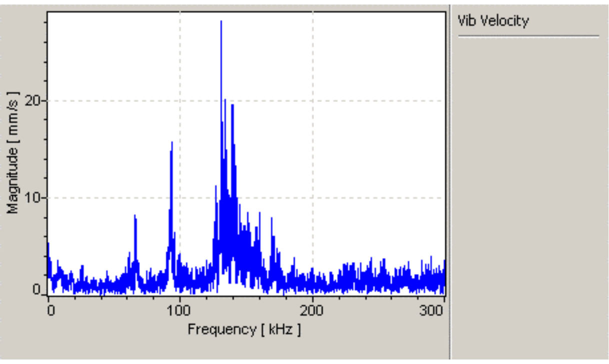

Figure 18: *FFT HD ID corner @ 0.540 atm on TE with drive with forward pivot, contact reached*

After this findings, addressing the problem and provide effective methods for solving it include right suspension / pivot point combinations, options for dampening key areas, and specially designed suspension's pivot dimples.

Sub-Nanometer Topographic Measurements on Media

Longitudinal magnetic recording technology is fast approaching and requiring new innovations in the recording media. The head geometries are shrinking as well as the critical media surface parameters affecting the flying height modulation (head/disk interface dynamics). A next critical step is to lower the flying height to near zero and use "Contact Recording" technique. For contact recording the current Angstrom level topography measurement techniques will no longer be sufficient and picometer resolution topography measurements will be required.

There are different methods available for media surface measurements such as Atomic Force Microscopy (AFM), Interferometry and Laser Doppler Vibrometry. With it's very low noise floor and with appropriate signal processing techniques [4,5] LDV has moved well beyond the resolution limitations of AFM and other optical methods. It has been demonstrated that resolutions of 0.01A (1pm) are achievable with modern LDVs.

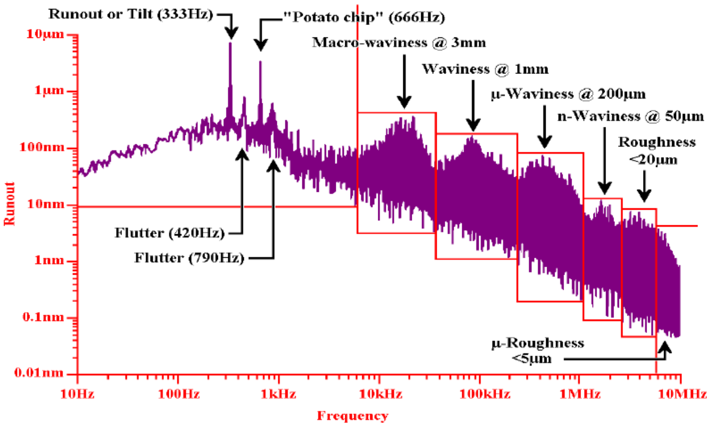

Figure 19: *Frequency content of the LDV signal and the relation to different surface parameters*

The spectrum is shown in figure X in the frequency domain is achieved from LDV measurements on the rotating media. Using Dual Channel LDVs both sides of the media can be measured simultaneously by traversing the laser beam across the media yields in a full area topography map.

Name	Symbol	Accuracy	Repeatability	Shortest Wavelength	Longest Wavelength
Nano-Roughness	nR	0.1Å	0.05Å	-	2μm
micro-Roughness	μR	0.1Å	0.05Å	-	5μm
Roughness	R	0.1Å	0.05Å	-	50μm
nano-Waviness	nW	0.1Å	0.05Å	50μm	100μm
micro-Waviness	μW	0.2Å	0.1Å	100μ	400μm
Waviness	W	0.5Å	0.25Å	400μm	2mm
Macro-waviness	MW	2.0Å	1.0Å	2mm	5mm

Table 4: *Surface topography definitions for HDD media*

Different surface properties are related to different LDV frequencies ranging from low frequency run-out modes <1KHz to micro- roughness with frequencies of 10MHz and higher.

The practical limit of the maximum frequency is given by the LDV's Bragg cell with 40 MHz modulation frequency. With such a system and HeNe laser a bandwidth of 20MHz (30MHz with some restrictions) can be achieved.

The waviness and roughness features are extracted from the LDVs analog output using bandpass filters to isolate the features shown in figure 19. Traversing the laser beam across the rotating media captures the full spectrum who's content can then be analyzed using PSD techniques to understand surface shape, distortion, polish, texture and finish.

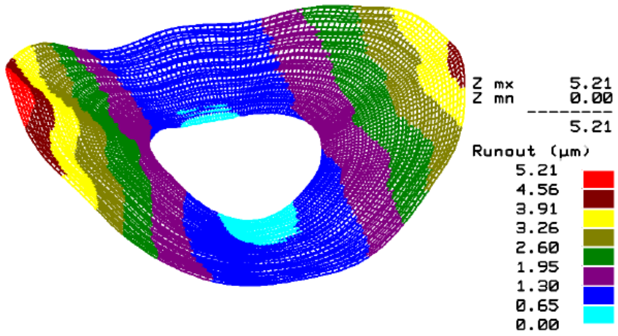

Figure 20: *Run-out and flutter of the media occurring a low frequencies <1kHz*

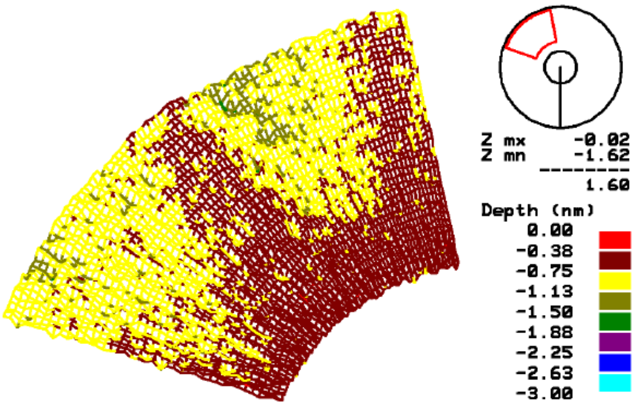

Figure 21: *Macro Waviness of a media section*

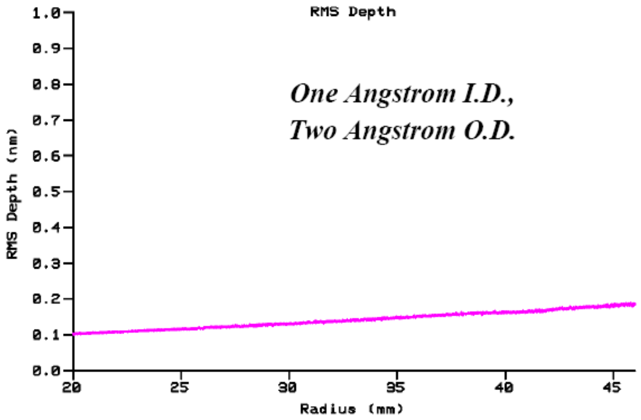

Figure 22: *μ-waviness as a function of radial position with topography features well below 1nm*

Future Outlook and Conclusions:

An overview of modern LDV signal processing methods has been given in this paper. Digital technology has certain advantages important for increasing performance demands in data storage industry. Right now, digital decoding methods cannot address all needs in terms of frequency and velocity. However with the availability of faster A/D converters and DSPs it can be expected that digital vibrometers will find access for more and more applications.

Digital demodulators with higher frequency bandwidth will be developed in the future as well as special software algorithms to compensate and handle group time delay. These decoders are required for many applications such as head-media interface studies.

Analog demodulation techniques will still be needed when it comes to very high frequencies. Media testing as mentioned in this paper requires 10MHz bandwidth and more, something that cannot be achieved with digital real-time techniques in the near future.

An expedient combination of different processing schemes, analog and digital, provides best performance and highest flexibility for different applications and will probably be the standard concept of future LDVs.

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