Vibration Measurement by a Laser Doppler Displacement Meter

by

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Abstract

The Laser Doppler Displacement Meter (LDDM) has been applied for the measurement of structure dynamics, such as resonance frequency, Bode plot, settling time, etc. in machine tools, rotary machinery, XY-stages, and servo controls. Other applications are in micromachining and in hard disk drive, such as flight height, head gimbal resonance, runout, etc. The basic principle of the LDDM, its comparison to laser interferometer and also vibrometer, major features and application are described.

INTRODUCTION

Recent rapid progress in microelectrical mechanical systems (MEMS) and high density hard disk drives (HDD), requires a sensitive, non-contact and small area vibration sensor. It is well know that the Doppler frequency shift of a laser beam reflected by a target is proportional to the velocity of the target, parallel to the direction of the laser beam. It is also known that the corresponding phase shift of the laser beam is proportional to the displacement of the target parallel to the direction of the laser beam. Based on this principle, the LDDM uses a laser beam, optical heterodyne, and a phase demodulator circuit to measure the phase shift Hence the displacement of the target can be determined. Because of the large signal-to-noise ratio, low reflectivity target or even diffusive reflecting target can be used. Also, a focus lens can be used to focus the laser beam to a small spot.

The LDDM™ vibration sensor measures the displacement at high resolution (2.5 nm) and high data rate (800,000 data/sec). It is non-contact, with a large stand-off distance, and the laser beam can be focused to a small spot. It is designed to capture the transient or CW phenomena of a motion. It performs as a storage oscilloscope for mechanical vibrations. Other applications are the measurement of dynamic properties, the vibration and resonance of a mechanical structure, the settling time of a precision stage, the run out of a spindle, the resonance frequency and damping of an optic table, the motion of a capillary bonder tip, and the runout, velocity and acceleration (RVA) of a disk drive.

THEORY OF OPERATION

The Laser Doppler Displacement Meter (LDDM) is a precision displacement measurement instrument based on the principle of Dopplometry (Wang 1987). Briefly, when a laser beam is reflected from a moving target, the Doppler frequency shift f_D is

$$f_D = f_L \left(2V/c \right) \qquad (1)$$

where f_L is the laser frequency, c is the speed of light and V is the target velocity parallel to the laser beam. Since frequency is the change of phase Φ with respect to time and velocity is the change if displacement x with respect to time, after one integration, Equation 1 becomes

$$\left(\Phi/2\pi \right) = 2 \left(f_L/c \right) \left(x - x_o \right) \qquad (2)$$

where Φ is the phase angle, x is the position and x_o is the initial position. Hence displacement x can be determined by measuring the phase angle Φ. When the phase changes more than 2π, a counter is used to keep track of how many 2π's.

The LDDM has an electro-optical device and phase-demodulator to measure the Doppler phase shift caused by the displacement of the target. For coherent detection, the target has to be a retroflector or a flat-mirror. However, recent progress in LDDM technology has improved the optical efficiency. It no longer needs a flat-mirror as a target, any polished surface or specular reflector, will be sufficient. For a diffusive surface, it is necessary to focus the beam to a small spot. A photo of a 2-axis LDDM vibration sensor is shown in Fig. 1.

A COMPARISON TO LDV VIBROMETER

The Laser Doppler Vibrometer (LDV), measuring the frequency shift of a moving target to determine the velocity of the target, is used for vibration measurement. The laser interferometer, counting fringes of a Michaelson interferometer (Downs 1989) to determine the displacement of the target, is used for precision displacement measurement. In some vibration measurement, it is more desirable to measure the displacement rather than velocity.

As compared to a Laser Dopplometry Vibrometer (LDV), based on Equation 1, the target velocity can be determined by measuring the frequency shift f_D. Any target with a rough surface of a diffusive reflector will scatter light back with the Doppler Shift caused by target velocity. The electro-magnetic field at the detector is the sum of lights scattered by many scatter centers. As shown by Wang (Wang 1988).

$$E(t) = \sum_{p=1}^{n} A_p \exp\{ -i2\pi (f_L + f_D) t + i\Phi_p \} \qquad (3)$$

where E (t) is the electro-magnetic field at the detector from n scatter centers, A_p is the amplitude, f_L is the laser frequency, f_D is the doppler frequency shift and Φ_p is the phase angle. After mixing with a local oscillator on a square law detector, the output spectral density has a term with the doppler frequency shift, f_D, and certain broadening. Because the light is scattered back, there is doppler ambiguity (Wang 1973) which broadens the frequency shift f_D and limits the detection to be above a certain minimum velocity of the target. Hence, for LDV the signal-to-noise ratio is low, a long averaging time is needed, and there is a minimum target velocity.

In summary, the major difference between the LDV and the LDDM are as follows:

1, **Electronics**
LDV: Frequency tracker, may tolerate momentary loss of signal.
LDDM: Phase-demodulator, error message if signal is below threshold.

2, **Signal to Noise Ratio, (S/N)**
LDV: Low and needs average over time, not suitable for transient events.
LDDM: High and no need to average, suitable for transient events.

3, **Target**
LDV: Scattering surface or diffusive reflector, may use reflecting tape to increase signal.
LDDM: Polished surface, scotch transparent tape, or focus lens for diffusive reflector at short range.

4, **Minimum Velocity**
LDV: Target needs to move above a minimum velocity, can not measure displacement.
LDDM: No minimum velocity, can measure displacement.

5, **Range Switch**
LDV: Several switch positions, dynamic range for each switch position is small.
LDDM: No switch, one large dynamic range.

The dynamic range of the LDDM vibration sensor is very large as shown in the range monograph (Fig.2). The whole range is in one setting and it is not a combination of several switch positions.

APPLICATIONS

The demand for higher total data storage capacity in smaller packages, is significantly pushing the hard disk technology. The track density becomes higher and the slider flight height becomes lower. Hence, better measurement of the static flight height, the dynamics of the slider during flight, take-off, landing, and the mechanical resonance of the slider and the slider suspension are required. The LDDM vibration sensors have been used for these applications.

For a flight height of 4 micro inches or less, a two-axis LDDM vibration sensor is used. One is focused at the disk and the other is found at the slider. The difference of these two readings is the flight height. For absolute flight height measurement, the distance is proportional to the measured phase angle Φ with an ambiguity of N (see Eq.2). As the slider lifts off the surface of the disk, the change in the phase angle is a direct measurement of the distance the slider has moved away from the disk. The distance d is

$$d = \left[\left(\frac{\varphi_1}{2\pi} + N_1\right) - \left(\frac{\varphi_2}{2\pi} + N_2\right) \right] \frac{c}{2 f_L}$$

$$= \left[\left(\frac{\varphi_1 - \varphi_2}{2\pi}\right) + (N_1 - N_2) \right] \frac{c}{2 f_L} \qquad (4)$$

where $(N_1 - N_2)$ is an unknown integer.

The ambiguity can be removed by knowing that the flight height is less than 100 nm. The resolution of the measurement is 2.5 nm and the frequency response is 800 kH_z.

The motion dynamics of a small hard disk drive rotating at 3600 rpm have been measured. As shown in Fig. 1 the first laser beam is reflected from the disk drive surface and the second laser beam is reflect from the back of the magnetic head. The disk drive is rotating at 3600 rpm and the focused laser beam spot size is 10 micrometer. The displacement measured by the first laser beam is shown in Fig.3. The periodic motion is the spindle run out. The maximum deviation is 0.2 micrometer.

The difference between the displacement measured by the first laser beam (disk run out) and the second laser beam (magnetic head or slider) is shown in Fig.4. The maximum deviation is 55 nm. The power spectra density of Fig.4 is shown in Fig.5 where a large peak at 300 H_z is the resonance frequency of the magnetic head motion. It is interesting to know that the power spectra density of the disk run out does not show any peak near 300 H_z.

SUMMARY AND CONCLUSION

The major features of the LDDM vibration sensor are:

1) High sensitivity and frequency response,
2) Non-contact, no wire attached and low interference,
3) Large dynamic range and wide band width,
4) No calibration constants, no non-linear amplifier, no RC time constant and no ringing frequency,
5) Compact,portable, and easy to set up,
6) Small beam spot diameter and variable stand off distance,
7) 2-channel for differential or orthogonal measurements, and
8) Absolute displacement, velocity and acceleration.

Because of the high sensitivity, high frequency response and simplicity, the vibration sensor can be considered as a mechanical oscilloscope which can view the sensitive mechanical vibration as easily as an oscilloscope to view the electrical signal. It will be an important tool for the study of mechanical structures and dynamics of motions.

REFERENCE

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FIGURE CAPTIONS

Fig. 1 - A photo of the LDDM Vibration Sensor

Fig. 2 - LDDM Sensor Range Nomograph

Fig. 3 - Spindle run out of a small hard disk drive rotating at 3600 rpm. The maximum deviation is 0.2 micrometer. Differentiate this displacement data once to obtain velocity and twice to obtain acceleration.

Fig. 4 - Magnetic head flight height variation. This is the difference of two displacement measurements. One is the disk and the other is the magnetic head. The disk is rotating at 2400 rpm and the magnetic head is at 0.6 inch from center. The peak-to-peak deviation is 50 nm.

Fig. 5 - Power spectra density of Fig. 4. A low frequency resonance at 300 H_z and several high frequency resonance near 1.4 kH_z.

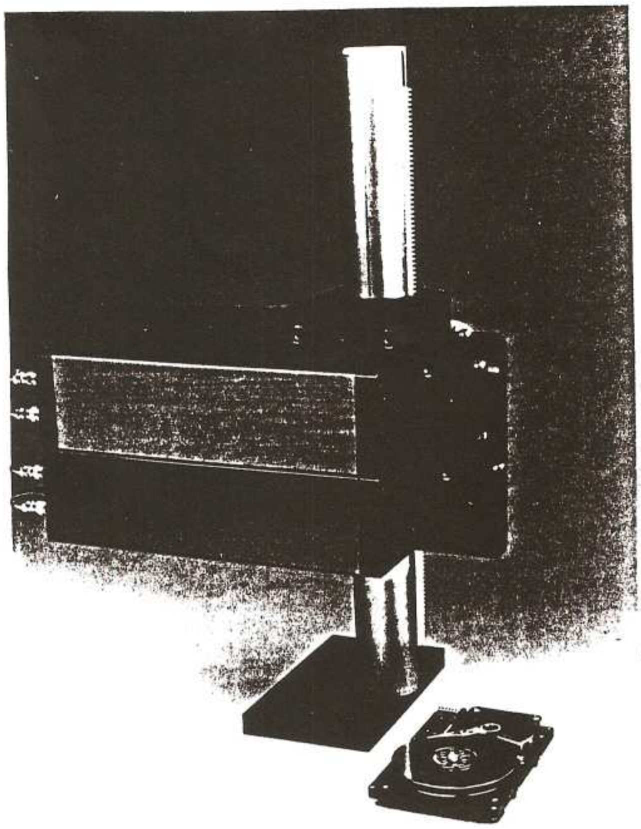


Fig. 1

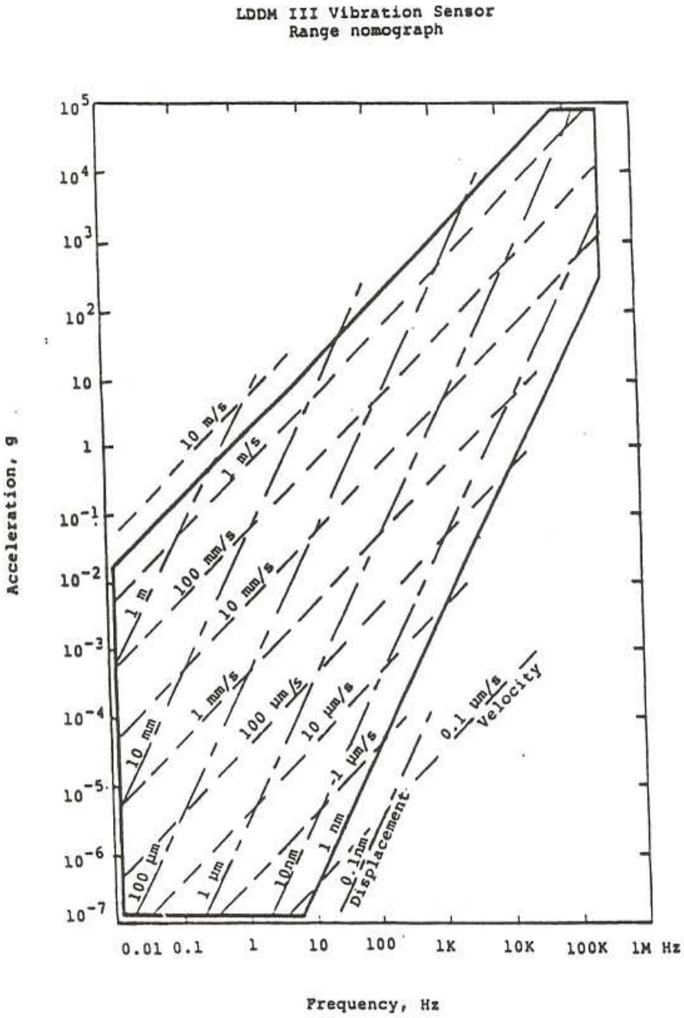


Fig. 2

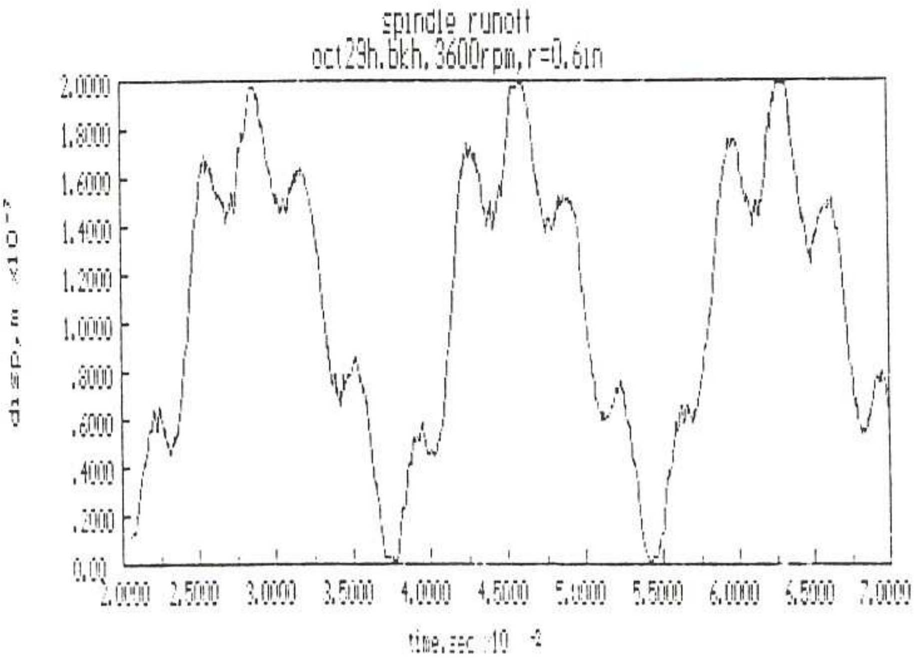
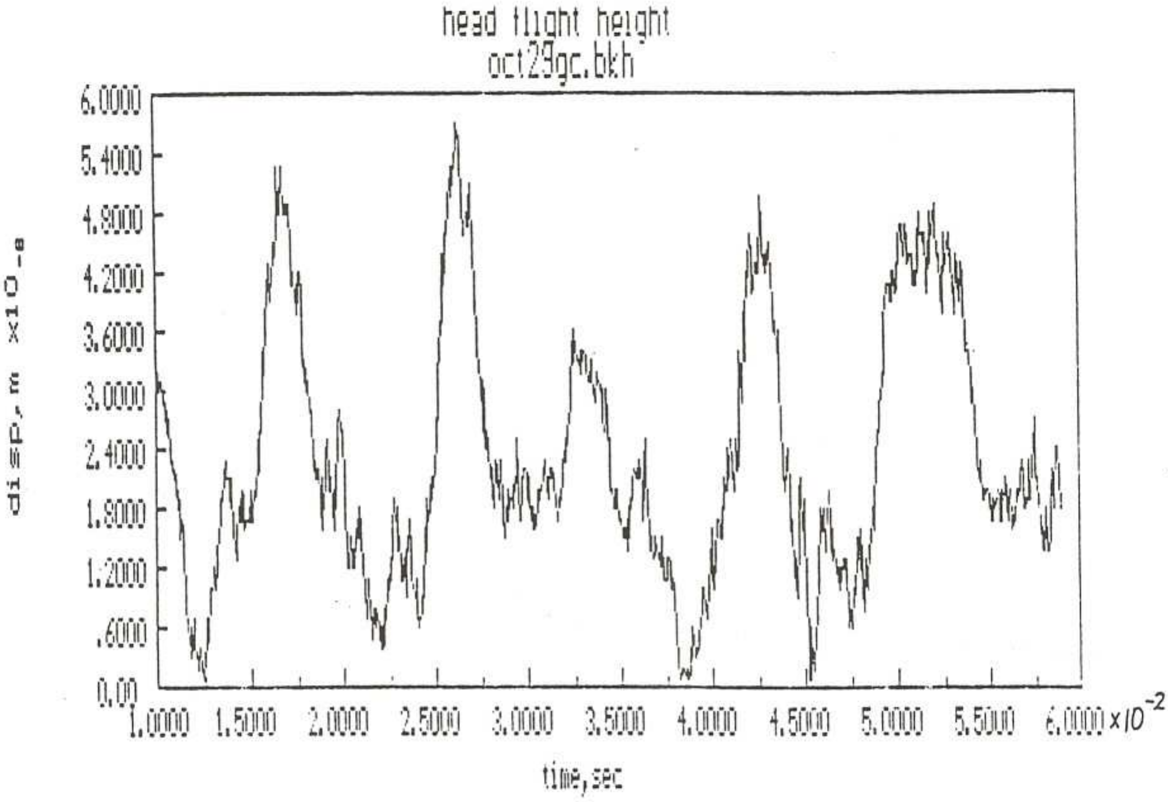


Fig. 3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1.5000
2.0000
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4.0000
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5.0000
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6.0000
x10^-2
time,sec

Fig. 4

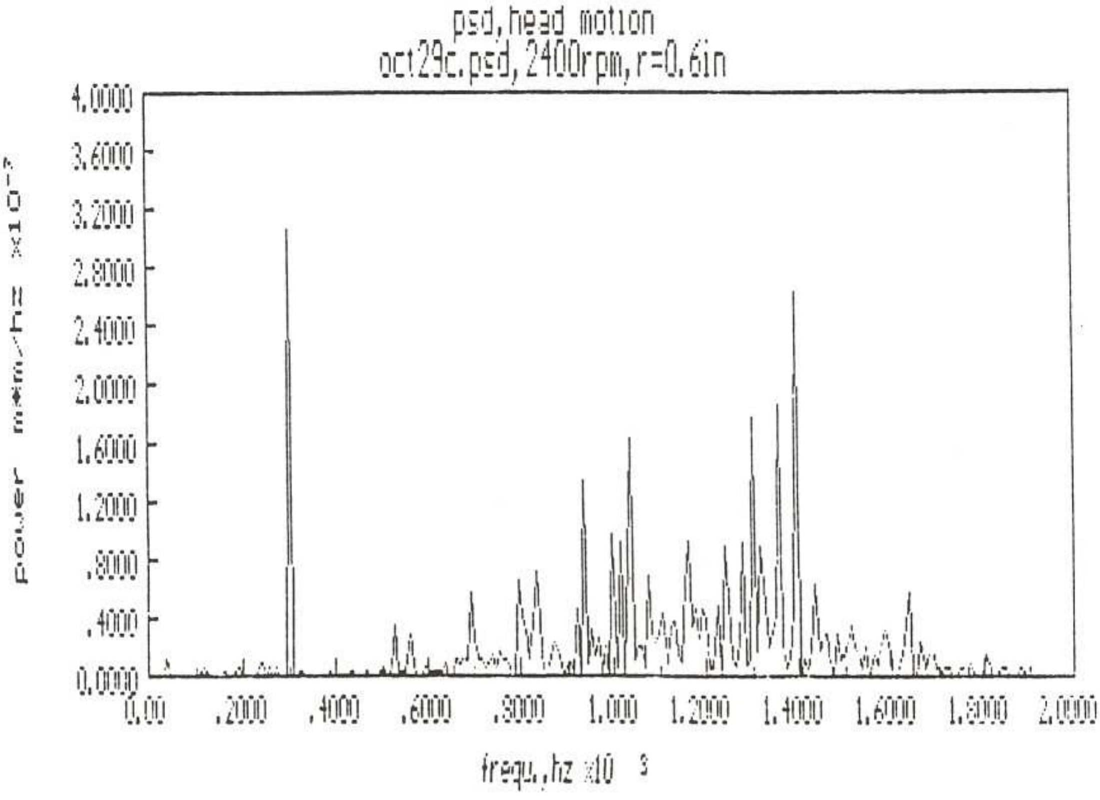
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Fig. 5