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A Runout Measurement Technology with Nanometer Resolution for Applications in Hard Disk Drives

J.C Huang, and C. Bi, *Senior Member, IEEE*

Abstract—Hard disk production needs accurate and fast measurement technology to qualify the spindle system produced. This paper presents several new technologies to measure the runout of spindle motor used in hard disk drives. The limitations of these technologies in the precise measurement are analyzed in the paper. The testing results show that, the technology utilizing optical interference is a good approach to realize 1 nano meter accuracy with high measuring speed. The experimental studies on different type micro motor are also presented.

Keyword: Spindle motor, runout, interference, vision, nanometer, resolution.

I. INTRODUCTION

THE increasing demand for computing and consumer devices with high storage density , faster read/write speed and more compact size hard disk drives (HDDs) is challenging HDD technology. Different type of HDDs, which includes the form factors form 0.85 to 3.5 inches and spindle speed from 3600 rpm to 20,000 rpm have entered market.

The high spindle speed is important in reducing the access time, but it also increases runout, vibration and acoustic noise of the HDDs, and affects the data recording density of the HDD. To meet the stricter performance requirements for HDDs, the spindle motor performance must be evaluated accurately and quickly in the HDD production, especially to the non-repeatable runout (NRRO) of the spindle system.

The spindle motors used in HDDs have the following trends:

(1) Low profile and compact structure.

(2) Using new kinds of fluid dynamic bearing (FDB), and will move to aerodynamic bearings (ADB), to reduce the NRRO, acoustic noise and cost.

Both above trends make the runout measurement be very difficult. In traditionally, the runout is measured by using the capacitor probe, and it is very effective to the motors with good conductive pass between rotor and stator. However, the conductive condition is quite poor in the FDB and ADB, and this makes the measurement results are easily corrupted by noise. For the capacitor probe, sensor area is critical in determining the sensing accuracy. Therefore the capacitor probe cannot be made with small dimension. In the application of the capacitor method, it can only be used to measure the spindle motor with form factor 2.5", or bigger than 2.5". How to measure the spindle motors with smaller form factor, e.g., 1.8", and even smaller, this is very concerned in HDD and spindle motor manufactures.

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Mr. Huang Jichang is a senior research engineer in the Data Storage Institute, Singapore, (phone: 65-68748411; fax: 65-67772053; e-mail: HUANG_Jichang@ dsi.a-star.edu.sg).

Dr. Bi Chao is a senior scientist in DSI. (e-mail: Bi_Chao@dsi.a-star.edu.sg).

A spindle motor runout measuring system using vision technology (RVM) has been developed in authors' laboratory and applied in HDD industry [2, 3]. For improving the resolution further, we utilize vision and interference technology to build iRVM system. These systems can measure the spindle motor repeatable runout (RRO) and NRRO in both axial and radial direction [4]. Compare to the conventional spindle motor runout measuring system, the major benefits in using RVM and iRVM include,

- Non-Contact Measurement;
- Rapid and automatic measurement for the RRO and NRRO in both axial and radial directions;
- There is no limitations in the bearing type, i.e., can measure ball bearing, FDB and ADB;
- Wide speed range
- High measurement accuracy. The accuracy of the RVM is 5 nm and iRVM is 1 nm;
- Measurement location self-learning
- Small sensor area requirement and can be used to miniature spindle motor and micro motor.
- Measurement result automatic compared with specification and failure alert.
- Measurement parameters can be program and recall.

II. RUNOUT MEASUREMENT UTILIZES VISION PATTERN RECOGNITION

The RVM is based on vision pattern recognition technology. The system is shown in Figure 1.

The vision pattern recognition utilizes a detector formed by microscope and CCD camera. The detector can collect the light from the whole image area simultaneously, and have a large dynamic range and controllable exposure times. These allow the system be able to get high signal-to-noise ratio images in the measurement, which are essential for the acquisition of high-resolution runout data signal.

Two issues were very concerned in the system design: resolution and sampling rate.

It is clear that spatial resolution of optic system is limited to approximately half the wavelength of light, according to the Rayleigh criteria, the resolution limit of a conventional microscope is given by

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Lateral:

$$d_{x,y} = \frac{0.61\lambda}{\text{NA}} \qquad (1)$$

and axial:

$$d_z = \frac{2\lambda}{\text{NA}^2} \qquad (2)$$

where λ is the wavelength of light, and NA is the numerical aperture of the lens.

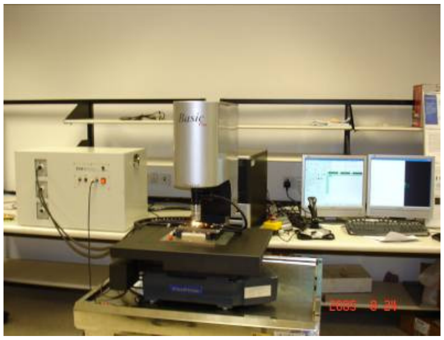


Figure 1RVM: Spindle motor runout measuring system based on vision pattern recognition technology

In order to improve the measurement resolution, a two-stage approach was developed and used in RVM. At the first stage, a computationally simple discrete template matching method is used to place the estimated edge point to the nearest pixel value. The second-stage method is designed for sub-pixel edge position estimation. The modified Chebyshev polynomial and the three-point interpolation method can be used easily in processing the edge pattern. If the functional form of the edge is known, a least-square estimation method may be used to get the better accuracy. In the case of non-stationary Poisson noise, a recursive maximum-likelihood method is proposed for the first-stage edge detection, followed by sub-pixel estimation. The sub-pixel edge detection algorithm can improve the measurement accuracy to 1/100 pixel resolution.

The normal CCD camera is not suitable as their sampling rate is less than the 50Hz. In order to realize the real time runout measurement, a fast image pattern generation method is developed. The method utilizes external synchronize signals trigger and only store the spindle motor edge image, the sampling rate can reach to 40KHz. Figure 2 illustrates the spindle motor image pattern.

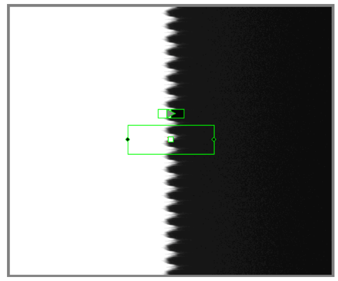


Figure 2 Spindle motor image pattern captured by CCD sensor

The measurement accuracy of RVM can get 5 nanometers. However, this accuracy is not enough for the new generation of HDDs as the NRRO will be lower and lower. Therefore, we had to explore the new technology to improve further the accuracy of the runout measurement system.

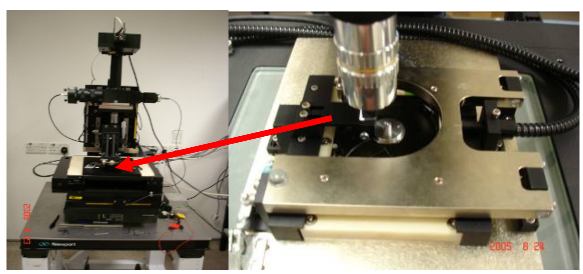
III. Measure Runout by Using Interference and Vision Technologies

The iRVM utilizes two high numerical aperture objective lenses and beam splitters to collect images from the same focal plane of reference mirror and object surface, and to let them interfere on a CCD plane, and this is the principle of the iRVM. Figure 3 illustrates the iRVM built in DSI's lab.

The intensity for the two-beam interference is equal to

$$I(x,y) = I_b(x,y) + \text{I}_\text{m}(x,y)Cos[\varphi_1(x,y) - \varphi_2(x,y)] \qquad (3)$$

where $I_b(x, y)$ is the background or the average intensity, and $I_m(x, y)$ is the intensity modulation; In traditional phase shifting interferometry, wave front reconstruction utilizes four or five images collecting in different reference phase during the measurement. However, the process is time consume and noise sensitive.



(a) (b)

Figure 3 (a) Spindle motor runout measuring system (iRVM) based on laser interference technology and vision technology. (b) HDDs and Fixture

Figure 4 shows four images recorded with a CCD camera for different positions of the pattern on the sample. The fringes are symmetry circle rings; it is clear that only use one row data which cross the circle center can express the whole image.

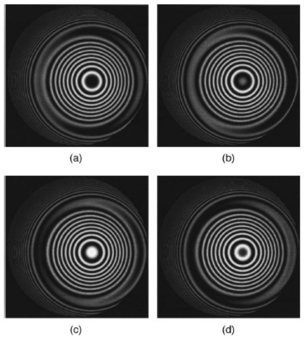


Figure 4 (a) Cosine of the phase, (b) sine of the phase, (c) negative cosine of the phase, (d) negative sine of the phase.

The vision pattern generation algorithm can be applied to iRVM. Every image line data can express interference fringe at spindle motor specific mechanic position. So the system only store one image line data and generate a vision pattern, Figure 5 illustrates that there is 512 measurement positions at one spindle revolution in axial direction.

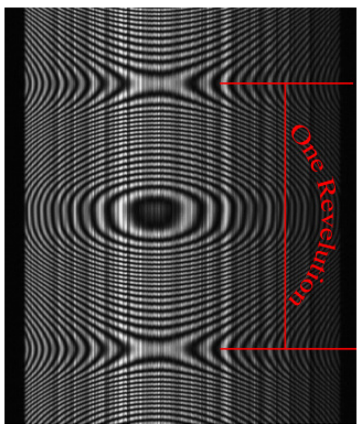


Figure 5 Spindle motor interference fringes

IV. Performance Analysis

The system resolution and uncertainty can be used to indicate the system performance.

The system resolution is the smallest incremental movement that the measurement can actually achieve.

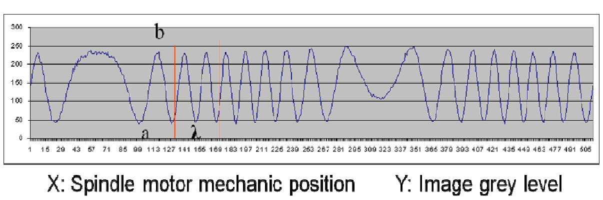


Figure 6 System measurement resolution of iRVM

The system measurement resolution can be analyzed in Figure 6. The two sine waves represent one wavelength. Thus, the distance from point (a) to point (b) is ¼ of a wavelength. If the camera is 8bits, and the interference light wavelength is 632nm. Thus the system resolution is less than 1 nanometer.

The uncertainty is a quantitative measure of the quality of a measurement result; enable the measurement results to be compared with other results, references, specifications or standards.

The uncertainty is estimated from real measurement result. The statistical tools give the assessment of uncertainties associated to the results only if all the relevant quantities involved in the process are interpreted or regarded as random variables [5].

The uncertainty is also can be used to evaluated the system performance with other measurement systems. The traditional spindle motor runout measurement systems are laser doppler velocimeter (LDV) and capacitance probe.

Table 1uncertainty measurement in various spin speed of hard disk drives

Frequency (rpm)	Uncertainty (nm)		
	iRVM	LDV	Capacitance Probe
3600	5.088508	14.38102	11.67939
4200	4.73736	20.4653	19.62571
4800	4.872504	19.90827	17.98761
5400	4.222199	10.85558	11.46451
6000	4.626834	11.01088	11.69568
6600	4.320094	11.14649	8.627105
7200	5.198161	17.90068	17.26213

There are many factors to influence the measurement data in the nanometer measurement, for example, temperature, air flow, environmental vibration etc. An experiment is set up to diminish the above disturbance. All the measurement data are collected synchronization and all instruments are installed on an anti-vibration stage. Table 1illustrates the uncertainty measurement of iRVM, LDV and capacitance probe.

The result shows the measurement performance of iRVM is better other measurement systems.

V. Experiments

Figure 7 illustrates one dimension wrapped phase signals and wave front phase unwrapped signals. The phase-reconstruction method using the line integration of the phase gradient is insensitive to the spatial non-uniformity of the illuminating beam and to the shape of the interferogram domain boundary. It exhibits a decreased sensitivity to the phase-shift errors and the non-uniformity of the detecting array pixels, as compared with the methods that calculate the arctangent function. The spindle motor RRO can thus be calculated by using a few half wave length sine signals, and NRRO can thus be known from the top and bottom of phase unwrapped signals, where, the pixel spatial resolution is quite high.

Figure 8 illustrates the spindle motor runout is calculated by using interference phase signal, and because the two sine wave of interference wrap phase signal is equal to one wave length, so the runout is counted on the number of sine wave.

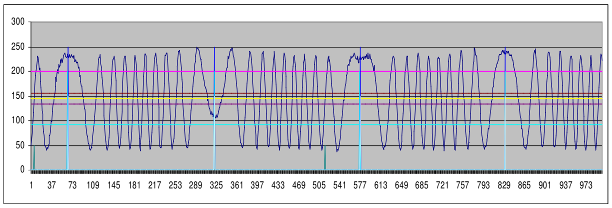


Figure 7 One dimension interference wrapped phase signal

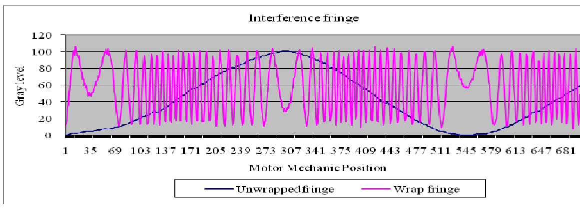


Figure 8 Interference phase signal unwrap to calculate runout

The Figure 9,Figure 10 and Figure 11 show the total runout, RRO and NRRO measurement results of a 2.5 inch hard disk drive respectively.

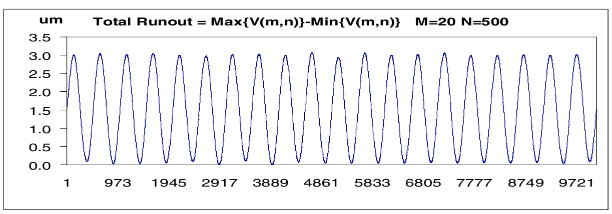


Figure 9 The runout measurement of 2.5 inch hard disk drive.

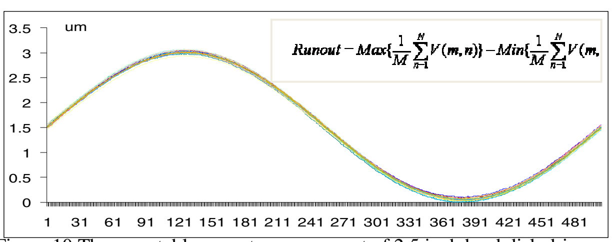


Figure 10 The repeatable runout measurement of 2.5 inch hard disk drive.

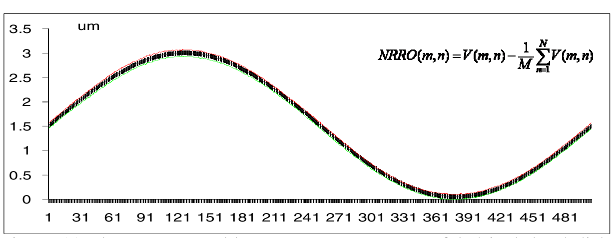


Figure 11 The non-repeatable runout measurement of 2.5 inch hard disk drive**.**

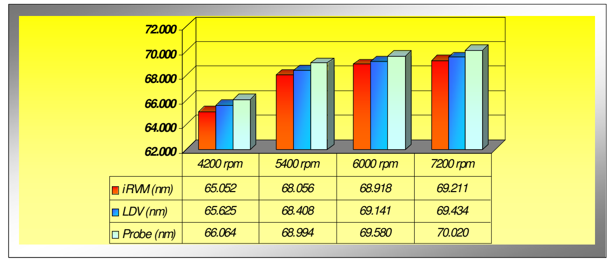


Figure 12 NRRO measurement of 1.8 Inch in 4200rpm using iRVM, LDV and capacitance probe.

Figure 12 illustrates the non-repeatable runout measurement of 1.8 inch hard disk drives using iRVM, LDV and capacitance probe. The NRRO is minimum under the specification (4200rpm).

VI. Conclusion

The applications and measurements have confirmed the effectiveness of RVM and iRVM in measuring and analyzing the runout of spindle system used in HDDs. RVM is based on vision edge detection technology, and iRVM is based on vision and optical interference technologies. For the systems developed, the former can realize 5 nm accuracy. They have become important tools in developing the new generation of HDDs. It is expected that these new measurement technologies can be further developed to get better measurement accuracy, and thus be applied to wider areas.

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