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Performance Analysis of the Vision Measuring Machine for Spindle Motor

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Abstract *–The runout measuring machine for spindle motor in hard disk drive (HDD) using vision technology has been developed. The runout measuring machine performance analysis is necessary to prove the confidence of the measurement data. The measuring machine performance analysis is based on the measurement system specification measurement data and international measurement standards. This paper briefly describes the vision measuring machine and some system specifications definition, such as total indicated runout (TIR), the repeatable runout (RRO) and the non-repeatable runout (NRRO) and system resolution. This paper also describes the measurement system performance evaluation factors, for example, resolution, accuracy, repeatability and uncertainty. Further more, we analyze influence system measurement performance elements during measurement and system development procedure. This paper also introduces an effective measurement method to avoid worst accuracy component. The traceable calibration is set up to decrease measurement uncertainty which improves the system performance.*

Keyword *Vision measuring machine, RRO, NRRO, Spindle motor, Performance, Uncertainty, Resolution, Accuracy, Repeatability.*

I. INTRODUCTION

The modern HDD tends to be lighter and more portable, runs at a high operating speed and possesses a high storage capacity. Vibration of spindle motor in the hard disk has received much attention recently. In addition, the dynamic characteristic of spindle motor becomes more complex. The diameter of the spindle motor in the has also smaller, the spindle motors in the hard disk drives with 1” form factor ones are already in production and the smaller ones are in preparation. The motors also run using a variety of different bearings such as fluid-dynamic bearings and ball bearings. In these cases, the traditional runout measuring system cannot keep up with the new requirements, for example capacitance probe and inductance probe which require large sensor area (3mm x 3mm) and small working distance (50 micrometers) and there is no space to install the probe. HDD and spindle motor companies are requiring new technologies to measure the RRO and n NRRO of spindle motor to determine the characteristics of spindle motors.

Compared with the traditional capacitance probe, the spindle motor runout vision measurement system has long working distance; the measuring parts can be easy load and unload resulting in a higher throughput. The capacitance probe has to be positioned very closely to the measuring surface. It is getting difficult to position capacitance probe very close to the spindle motor due to the decreasing size of the HDD. In this case, the vision sensor can be efficiently used because it does not have to be closely positioned.

The measuring machine for spindle motor using vision technology has been successfully developed, [1]. The vision measuring machine for spindle motor is shown in Figure 1.

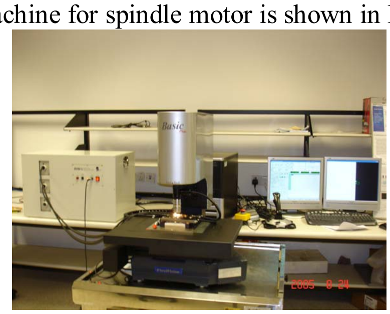

Figure 1 The vision measuring machine for spindle motor

The system utilizes a spindle motor driver to drive the spindle motor, the spindle motor driver generates the back-EMF zero-crossing signals, the back-EMF zero-crossing signals trigger the CCD camera, the CCD camera captures some images of the spindle motor at the same position every rotation. The CCD pixel sample rate is 40 MHz. A control program adjusts the illuminator to ensure a consistent lighting condition during the measurement procedure. The sub-pixel edge detection and auto-focus image processing algorithms were used to detect spindle motor position. [2]

The pattern image of rotating spindle motor is shown in Figure 2. The RRO and NRRO of the spindle motor can be calculated by detecting the pattern image white to black edge position data. The system resolution reaches to nanometer level.

Figure 2 The pattern image of rotating spindle motor in multi-cycles

This paper analyzes the performance vision measuring machine for spindle motor, and this will prove the confidence of measurement data.

II. SPINDLE MOTOR RUNOUT DEFINITION

There are three parameters that describe the spindle motor dynamic characteristic; they are total indicated runout (TIR), repeat runout (RRO) and non repeat runout (NRRO). When TIR is sampled with N numbers spindle motor back-EMF zero-crossings per revolution over M revolutions, TIR(m,n) can be defined as the total indicated runout corresponding to the nth sector of spindle motor at the mth revolution. RRO(n) is independent of *m* because it is repeated at each revolution so that TIR(m,n) can be written as follows.

$$TIR(m,n) = RRO(n) + NRRO(m,n) \quad (1)$$

The *RRO(n)* is the repeat runout at nth back-EMF zero-crossings sector of spindle motor, which is obtained by averaging the TIR(m,n) over total M revolutions, i.e.,

$$RRO(n) = \frac{1}{M}\sum_{1}^{M} TIR(m,n) \quad (2)$$

So, the NRRO(m,n) is calculated from as following:

$$NRRO(m,n) = TIR(m,n) - RRO(n) \quad (3)$$

The TIR is calculated by

$$TIR = \text{Maximum}(TIR(m,n)) - \text{Minimum}(TIR(m,n)) \quad m = 1\ldots M,\ n = 1\ldots N \quad (4)$$

The RRO is calculated by following equation

$$RRO = \text{Maximum}(RRO(n)) - \text{Minimum}(RRO(n)) \quad n = 1\ldots N \quad (5)$$

The standard deviation σ of NRRO(m,n) is calculated as following:

$$\sigma = \frac{1}{M \times N}\sqrt{\sum_{m=1}^{M}\sum_{n=1}^{N}(NRRO(m,n))^2} \quad (6)$$

$$NRRO = 6x\ \sigma \quad (7)$$

The NRRO is expressed calculated by equation (7) . The Figure 2 illustrates TIR(m,n), RRO(n) and NRRO(m,n) in time domain measurement for a sample fluid bearing spindle motor using the vision measuring machine.

In additional, the NRRO can also be calculated in the frequency domain. The total power of the NRRO can be obtained by measuring the area under its power spectral density or by summing all the components of its power spectrum.

$$PSD_m(f) = 4\int_{\sigma}^{\infty} R_m(\tau)\cos(2\pi f\tau)d\tau \quad 0 \le f \le \infty \quad (7)$$

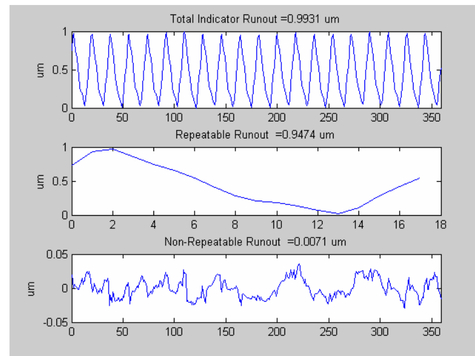

Figure 2 TIR, RRO,NRRO measurement data in time domain

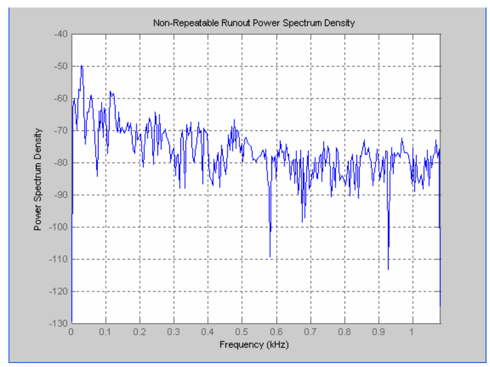

Figure 3 NRRO measurement data in frequency domain

Figure 2 illustrates TIR, RRO and NRRO in time domain for a sample fluid bearing spindle motor. Figure 3, illustrate the NRRO in frequency domain respectively for the same spindle motor. The spindle motor operating speed was 90 Hz. TIR was measured over 20 revolutions, and 18 data points per revolution were sampled by the back-EMF zero-crossing signals generated from a motor driver.

The vision measuring machine performance will be analyzed based on the NRRO measurement result and measurement system performance evaluation factors, for example, resolution, accuracy, repeatability and uncertainty, according to the international standard.

III. MEASUREMENT PERFORMANCE FACTORS

This paper analyzes various factors which influence system data confidence. The discussion is according to following international standards.

- **ISO 23060-2**
- **ANSI B5.54**
- **ANSI B89**

- **VDI 3441**
- **VDI 2617**
- **JIS-B6330**
- **GB-10931-89**

For discussing the system measurement performance, it is necessary to clarify some basic concepts in the measurement procedure; they are ***resolution***, ***accuracy, repeatability*** and ***uncertainty*** which definition can be found in the above standards.

These terms are the fundamental parameters of positioning systems. Unfortunately, they are often used synonymously with resulting confusion on the part of users and vendors alike.

- Resolution: It is the smallest incremental movement that the measurement system can actually achieve.
- Accuracy: provides a measure of how well a positioning system moves relative to an absolute frame of reference.
- Repeatability: provides a measure of how well a positioning system moves relative to its own frame of reference.
- Uncertainty: is a quantitative measure of the quality of a measurement result.

The repeatability of a positioning measurement system is the extent to which successive attempts to move to a specific location vary in position. A highly repeatable system (which may or may not also be accurate) exhibits very low scatter in repeated moves to a given position, regardless of the direction from which the point was approached. Figures 4a, 4b, and 4c illustrate the difference between repeatability and accuracy. For spindle motor measurement, short-term measurements which reflect the intrinsic properties of the spindle motor.

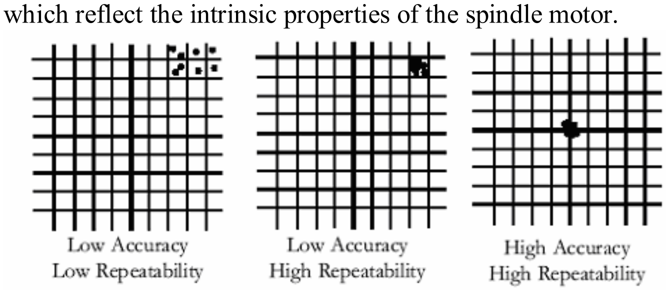

Figure 4 A, B, C: Accuracy vs. Repeatability

Uncertainty is a quantitative measure of the quality of a measurement result, enabling the measurement results to be compared with other results, references, specifications or standards.

The precision of a measurement can be described as the ability to cluster measurements about some underlying points. The spread of this cluster limits the ability to differentiate between two nearby measurements. Thus, precision is often associated with the resolution of a measurement.

All measurements are subject to error, in that the result of a measurement differs from the true value of the measurement. Given time and resources, most sources of measurement error can be identified, and measurement errors can be quantified and corrected, for instance through calibration. There is, however, seldom time or resources to determine and correct completely for these measurement errors.

IV. SYSTEM PERFORMANCE ANALYSYS

We analyze the factors which influence the measurement system performance in the following section; the factors are noise floor, mechanical vibration, temperature and humility etc.

Although we have illustrated how the vision measurement machine for spindle motor might calculate displacements much smaller than a pixel [2], the limitation on the measurable magnitude of these displacements is set by the noise floor of the instrument.

Mechanical vibrations and variations in the illumination contribute principally to the raising of the noise floor and influence the different types of the measurements to different degrees. So the measurement algorithms developed will independent on stage motion to avoid the mechanical measurement error. The NRRO measurement errors will be independent on the mechanical vibration due to measuring algorithm design. This is because the measurement based on CCD camera field of view pixel coordination system and is not relation with the stage absolution coordination system.

The resolution, accuracy are indicators of measurement system performance.

Figure 5 reveals the spindle motor radial and axial axes NRRO noise measured by the vision measuring machine for spindle motor. The average is 2.038 nanometers (nm) and 1.653 nm respectively; standard deviation is 0.795nm and 0.695nm respectively. This figure highlights at least a couple of important points: First, the absolute noise floor is quite low, rarely greater than a few of nanometers. Second, the system is capable of sensing very small disturbances in the environment.

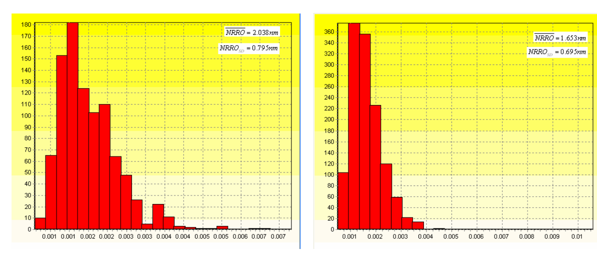

Figure 5 Spindle motor radial and axial NRRO noise measurements

Figure 5 illustrates the ability to obtain the same displacement measurement for a series of measurements which describes the repeatability of the vision measuring machine for spindle motor. Displacements were calculated using the identical image data set used for noise floor measurements for a single region of interest selected.

Figure 5 shows the vision measuring machine resolution is less than the 5 nanometers.

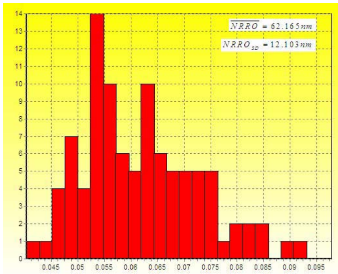

Figure 6 NRRO 100 times measurement probability density function

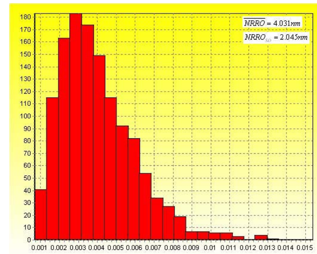

Figure 8 Spindle motor NRRO measurements at 28 degree temperature, without anti-vibration condition

Here, we have defined precision as the scatter of measurement spindle motor NRRO. Figure 6 shows the NRRO measurement probability density function for 100 measurements. The mean standard deviation of the scatter component is 12.103 nm. Figure 6 illustrates the accuracy of vision measuring machine for spindle motor reaches 12 nanometers after the machine calibrated.

The reproducibility of a measurement further describes the vision measuring machine for spindle motor measurement performance.

The reproducibility of a measurement speaks to the ability to take two measurements at two different times under similar (but not necessarily identical) conditions and to get the same answer. The NRRO measurements from the initial eight hour data set were compared to independent measurements taken two days later.

The plots in Figure 7, the initial set of measurements (left) are shown along with the measurements taken two days after (right) in the plots of while the difference between these measurements (mean of initial set minus measurement two days later) is 1.176nm. The root-mean-square of these differences is 0.593nm. Figure 7 illustrates the spindle motor NRRO measurement result is the same in spite of the measurement period.

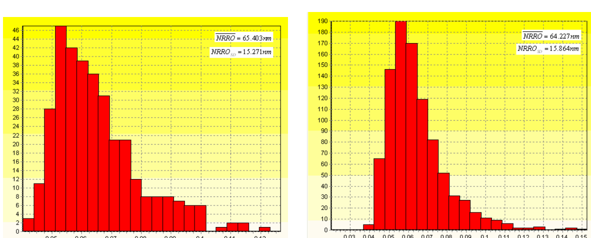

Figure 7 Spindle motor NRRO measurements at different periods

The environment factor will influence the measurement resolution and measurement reproducibility; the temperature and humidity need to be kept the constant during the production inspection procedure.

Figure 8 illustrates the NRRO measurement under the 28 degree temperature and without the anti-vibration table condition, the average is 4.031nm and standard deviation is 2.045 nm, the result is worst than the one is shown in Figure 5.

The above the discussion has proved the vision measuring machine performance. In additional, the calibration of vision measuring machine improves the measurement system accuracy.

Three main reasons for having a measuring system calibrated:

1. To ensure readings from the system are consistent with other measurements.

2. To determine the accuracy of the measuring system readings.

3. To establish the reliability of the measuring system i.e. that it can be trusted.

A basic tool in ensuring the traceability of a measurement is the calibration of a measuring system or reference material. Calibration determines the performance characteristics of an instrument or reference material. It is achieved by means of a direct comparison against measurement standards or certified reference materials.

Reference procedures can be defined as procedures for testing, measurement or analysis, thoroughly characterized and proven to be under control, intended for quality assessment of other procedures for comparable tasks, or characterizations of reference materials including reference objects, or determination of reference values.

The vision measuring machine for spindle motor has two calibration procedures; one is measuring stage linear, non-linear, perpendicular between the stage axes calibration, another is calibration of the sensor pixel.

The spindle motor NRRO is measured after calibration and the results are shown in figure 9.

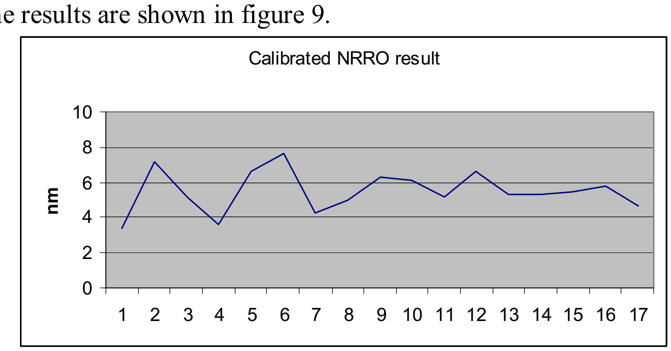

Fig9 Spindle motor NRRO result after calibrated.

CONCLUSION

We have discussed measurement system resolution, accuracy and reproducibility through experiment results.

The vision measuring machine for spindle motor is suitable for using as a non-contact measurement device to measure small spindle motors. The sensor area is around 10um x 10um (adjustable). So the vision measuring machine for spindle motor can measure all types spindle motor (ball bearing motor, fluid bearing motor, etc.) and different spindle motor sizes (0.85inch~3.5inch form factors). The vision measuring machine for spindle motor can be realized automatic measurement.

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