An Application of Michelson Laser Interferometer for Roundness Measurements

Chana Raksiri^{1,2}, Thitipoom Dorkyor¹

¹Department of Industrial Engineering, Faculty of Engineering, Kasetsart University

²Research and Development Institute of Production Technology, Faculty of Engineering, Kasetsart University, Jatujak, Bangkok 10900, Thailand,

Tel: 662-942-8566-70 Fax 662-942-8571 *E-mail: fengcnr@ku.ac.th

Abstract

This research proposes a new application of Michelson laser interferometer for roundness measurement. Michelson laser interferometer is the high precision length measurement in the resolution of one nanometer. The optical setup is described and the theory is derived. This measurement system composes of laser interferometer, a single-axis rotary table and a glass hemisphere. The roundness of glass hemisphere is the result of this experiment where are located and rotated by single-axis rotary table. A laser interferometer reflector mirror is placed on moving slide which can move along the glass hemisphere surface. The displacement of reflector along glass hemisphere results to the radius of glass hemisphere at each sampling angle. The uncertainty of this system is determined from the laser interferometer uncertainty, rotary table uncertainty and environment. Experimental results show that the roundness, refer to The Japan International Standard (JIS) roundness measurement result of the glass hemisphere is $0.223 \mu\text{m}$ and measurement uncertainty $\pm 0.0814 \mu\text{m}$. The roundness of this glass hemisphere from convectional method is $0.06 \mu\text{m}$. Experiment results show the proposed approach can be applied for roundness measurement.

Keywords: Roundness measurement, Laser Interferometer, Uncertainty, Michelson's interferometer

1. Introduction

Roundness is one of the basic geometric of a mechanical object. The departure of a feature from roundness is defined to be the difference between its maximum and minimum radial ordinates. However, due to imperfections introduced by the manufacturing process, the feature produced will never be truly circular or not easy to do. Variations on circular features may occur due to imperfect rotation, erratic cutting action, inadequate lubrication, tool wear, defective machine parts, chatter, and misalignment of chuck jaws etc.

When demand for workpiece roundness measurement to nanometer accuracy is increasing. Features thus have to be inspected to determine whether a certain degree of roundness has been attained. To increase the accuracy of manufacture, measuring capabilities must be improved significantly.

There are many propose method to measuring roundness. Chen [7] applied machine visions for discontinuous perimeters roundness measurement. Gao et al.[8] presented the possibility of using fewer probes to realize the mixed method and proposed an optimum mixed method called the orthogonal mixed method.

For many years, the performance of the laser interferometer systems exceeded the requirements of the manufacturing equipment. It is the high precision length measurement in the resolution of 1 nanometer instrument. They are widely used due to the advantages of high signal to noise ratio, high linearity and direct measurement. Lin [9] presented the straightness measured by laser interferometer.

This paper presents an application of Michelson laser interferometer for roundness measurement of standard

glass hemisphere, which composes of laser interferometer and a single-axis rotary table. They are another way to measuring the workpiece roundness with the accuracy $0.01 \mu\text{m}$.

2. Roundness Measurements

2.1 Methods for obtaining deviation from roundness

Roundness is usually assessed by rotational techniques by measuring radial deviations from a rotating datum axis; this axis remains fixed and becomes the main reference for all measurements. There are two common ways of measuring roundness. One method involves rotation of the part while keeping the measuring transducer fixed, as apply in this research, and the other involves keeping the component fixed while rotating the measuring transducer.

Measuring differences in diameter is not sufficient to measure roundness. For example, part as shown in Fig.1 has a constant diameter when measured across its centre, but is clearly not rounded. To measure any component for roundness we require some form of datum [10].

Figure 1: A constant diameter part [10]

In this research, the experiment refers to reference standard “The Japan Industrial Standard (JIS) roundness measurement” which describes the roundness of the workpiece, is “The deviation from ideal roundness is assessed as the difference between the largest and the smallest radii of the profile measured”, relative to the following centre:

a) Least squares centre (LSC) – the centre of the least squares mean circle

b) Minimum zone centre (MZC) – the centre of the minimum zone circle

c) Minimum circumscribed circle centre (MCC) – the centre of the minimum circumscribed circle for external surfaces

d) Maximum inscribed circle centre (MIC) – the centre of the maximum inscribed circle for internal surfaces

The largest and smallest radii in each case are commonly used to define a concentric zone. The width of the zone (designated by Δz) denoting the measured profile of the workpiece centre.

For this purposes Least squares centre as shown in Fig. 2. is used for determine the circle center.

Figure2: Assessment of roundness from least square center [5]

2.2 Determination of least squares centre and circle

From the center of the chart as shown in Fig. 2., the twelve sufficient even number of equally spaced radial line are drawn on the chart (Line number 1 to 12) The intersection points (P_1 to P_{12}) between polar graph and radial lines are measured along x and y axes, taking positive and negative signs into account, in rectangular coordinate system. The distances a and b of the least squares centre from the centre of the chart are given by the following approximate equations:

$$a = \frac{2 \sum_{i=1}^n x_i}{n} \quad (1)$$

$$b = \frac{2 \sum_{i=1}^n y_i}{n} \quad (2)$$

Where, $\sum_{i=1}^n x_i$ is the sum of all x values.

$\sum_{i=1}^n y_i$ is the sum of all y values.
n is the number of radial line.

If required the radius, R of the least squares circle is given by the equation:

$$R = \frac{\sum_{i=1}^n r_i}{n} \quad (3)$$

Where, $\sum_{i=1}^n r_i$ is the sum of radial of points P from the least squares centre.

After the center of the least square is approximated, the roundness value can be determined by calculation from the difference between the maximum radius and the minimum radius of the least square circle. These radii mean to distances between the least square center and each experiment results. These distances are given by the equation (4)

Figure3: Determination of least square center and circle [5]

$$R_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \quad (4)$$

Where, R_i is radius of the least square circle.

X_i, Y_i is the coordinates of each experiment results point.

X_0, Y_0 is the coordinates of the least square center.

When the maximum radius and the minimum radius of the least square circle can be approximated from the given equations

$$R_{\min} = \min(R_i) \quad (5)$$

$$R_{\max} = \max(R_i) \quad (6)$$

Where,

$R_{\min}$ is the minimum radius of the least square circle.

$R_{\max}$ is the maximum radius of the least square circle.

So the roundness value can be determined by the equation (7)

$$\Delta R = R_{\max} - R_{\min} \quad (7)$$

Where, ΔR is the roundness value.

3. Laser Interferometer

The Michelson laser interferometer is composed of a single-frequency class II low power Helium-Neon laser with wavelength 632.9 nanometer, a laser wavelength environmental compensation unit due to the effect of air temperature, air pressure and relative humidity.

In general, such an interferometer comprises four important parts: a laser source, beam splitter, a reflector, and a light receiver. The beam splitter first converts two co-axial (or parallel) beams coming from the laser source into two divergent beams as shown in Fig. 4.

Figure 4: Michelson laser interferometer

These two divergent beams are then incident onto the reflector, which reflects the incoming beams back into the beam splitter and then into the receiver. When the reflector is moved along with the stage, the interference signal detected by the receiver can be adopted to determine the lateral movement of the stage. [3]

4. Uncertainty of Measurements

The uncertainty analysis of this purpose is accordant with the ISO *Guide to the Expression of Uncertainty in Measurement*, which estimation of uncertainty components can be done in two different ways.

4.1 The standard uncertainty Type A, u_A

Type A evaluation is evaluation of uncertainty components using statistical means.

The standard deviation of the distribution or the standard deviation of the mean can be calculated from repeated measurements data by using the following formulas:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (7)$$

The mean value of a number n of measurement results x_i

$$s_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (8)$$

The standard deviation of the distribution of the sample based on n measurement values

$$s_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n \cdot (n-1)}}$$

$$\text{or } s_x = \frac{s_x}{\sqrt{n}} \quad (9)$$

The standard deviation of the mean values of the sample is equal to the standard deviation of the sample divided by the square root of the number of measurements n .

The standard deviation of the mean values is the value used for the standard uncertainty Type A, u_A .

$$u_A = s_x = \frac{s_x}{\sqrt{n}} \quad (10)$$

4.2 The standard uncertainty Type B, u_B

Type B evaluation is evaluation of uncertainty components by any other means than statistical. It can be evaluated by scientific judgement based on all available information on the possible variability. Values belonging to this category may be derived from:

- previous measurement data
- experience with or general knowledge of the behaviors and properties of relevant materials and instruments
- manufacturer's specifications
- data provided in calibration and other certificates
- Uncertainties assigned to reference data taken from handbooks.

When a probability distribution can be assumed for the input quantity, based on theory or experience, then the appropriate expectation or expected value and the square root of the variance of this distribution have to be taken as the estimate $\bar{x}$ and the associated uncertainty Type B, u_B , respectively

If only upper and lower limits a^+ and a^- can be estimated for the value of the quantity x_i (e.g. manufacturer's specifications of a measuring instrument, a temperature range, a rounding or truncation error resulting from automated data reduction), a probability distribution with constant probability density between these limits (rectangular probability distribution as shown in Fig. 5.) has to be assumed for the possible variability of the input quantity. According to above this leads to

Figure: 5. Rectangular distribution used for transforming limits of variation into uncertainty component [2]

$$\bar{x} = \frac{1}{2}(a^+ + a^-) \quad (11)$$

for the estimated mean value and

$$\sigma^2 = \frac{1}{12}(a^+ - a^-)^2 = u_B^2 \quad (12)$$

for the variance which is equal to the square of the standard uncertainty. If the difference between the limiting values is denoted by $2a$, equation (3.7) yields [2]

$$u_B = \frac{1}{\sqrt{3}}a \quad (13)$$

4.3 Combined standard uncertainty

The combined standard uncertainty of a measurement result, suggested symbol u_c , is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties u_i , whether arising from a Type A evaluation and a Type B evaluation, using the usual method for combining standard deviations. This method is often called the law of propagation of uncertainty and in common parlance the "root-sum-of-squares" (square root of the sum-of-the-squares) or "RSS" method of combining uncertainty components estimated as standard deviations. The combined standard uncertainty can be approximated from the given equations

$$u_c = \sqrt{u_A^2 + u_B^2} \quad (14)$$

5. The proposed architecture

This paper proposes an application of Michelson laser interferometer for roundness measuring system. This measurement system composes of laser interferometer, a single-axis rotary table and standard glass hemisphere as shown in Fig. 6.

Figure: 6. The roundness measurement system

The contact probe and reflector mirror are placed on moving slide which can move follow with the hemisphere surface as shown Fig. 7. The glass hemisphere is located in the center of table and rotated with incremental angle by the single-axis rotary table as shown in Fig.8. The displacement of laser interferometer reflector which move follow with moving slide along the glass hemisphere surface results in Michelson laser beam interference, mean to the radius of glass hemisphere at each incremental rotary table angle from 0 to 360 degree.

Figure: 7. The reflector mirror is placed on moving slide

Figure: 8 The glass hemisphere is located on single-axis rotary table

6. Experiment and result

The rotary table was rotated from 0 to 360 degree, with 10 degree interval angle. The radius of glass hemisphere data was measured for each angle. Eight times roundness measuring were done for this experiment. The thirty five radius of glass hemisphere data were used to evaluate the roundness of the glass hemisphere as explained in equation (1) to (3). At 0 degree, the reference angle, the moving slide was moved to touch the hemisphere surface. The laser interferometer was set to zero. The results are showed in Table 1

Table 1 shows the results from eight run of the experiment. First column shows number of each run and the average result in last row. The second and third columns show the coordinate (a , b) of the least square center. The fourth column shows the least square radius (R). The fifth and sixth columns show the maximum ($R_{\max}$) and minimum ($R_{\min}$) distances from the least square center to each point on trace. And the last column shows the roundness value (ΔR).

Table1

No.	a	b	R	R_i		ΔR
				$R_{\max}$	$R_{\min}$	
1	-0.148	-0.026	0.136	0.223	0.055	0.169
2	0.100	-0.071	0.138	0.262	0.044	0.217
3	0.093	-0.128	0.133	0.260	0.012	0.248
4	0.112	-0.065	0.121	0.265	0.023	0.252
5	0.091	-0.080	0.142	0.265	0.029	0.237
6	0.089	-0.104	0.140	0.267	0.006	0.261
7	0.096	-0.084	0.133	0.253	0.010	0.243
8	0.107	-0.098	0.125	0.277	0.024	0.253
Avg	0.100	-0.086	0.130	0.248	0.024	0.223

Then, the rotary table was rotated 10 degree and collected the difference of optical length. The rotary table was rotated and collected radius of glass hemisphere data until completely 360°. Figure.8 shows the polar plot of experiment measuring results.

The average roundness from eight of experiment time is 0.223 μm .

The measurement uncertainty components can be divided into;

-The standard uncertainty Type A, which can be calculated from results of each experimental. That is 0.006969 μm

- The standard uncertainty Type B, these errors budgets comprise the following components;

Figure: 9 The Polar Plot of Experiment results

6.1 Uncertainties intrinsic to the system

6.1.1 Measurement System Accuracy is generally specified in part-per-million (ppm) and the resulting measuring error is a function of the distance measured by the laser interferometer. For this case it is ± 1.1 ppm. or ± 0.0011 μm . Therefore;

$$u_1 = \frac{0.0011}{\sqrt{3}} \\ = 0.000635 \mu\text{m}$$

6.1.2 Uncertainty of measurements; ± 0.025 μm , with coverage factor, $k = 2$

$$u_2 = \frac{0.025}{2} \\ = 0.0125 \mu\text{m}$$

6.1.3 Resolution; 1 nm

$$u_3 = \frac{0.001}{2\sqrt{3}} \\ = 0.000289 \mu\text{m}$$

6.2 Uncertainties due to Material thermal expansion

Correction for expansion (or contraction) may be necessary due to the variation of dimensions of the machine caused by temperature changes. This correction relates the distance measurement back to a standard temperature of 20 °C. When 0.2 °C changes in air temperature and the coefficient of thermal expansion for steel is 11.5×10^{-6} mm, then the uncertainty can be calculated from;

$$u_4 = \frac{0.2233 \cdot 11.5 \times 10^{-3} \cdot 0.2}{2\sqrt{3}}$$

$$= 0.002966 \text{ } \mu\text{m}$$

6.3 Uncertainties due to the rotary table

6.3.1 Relative Error of Measured Magnification

6.3.1.1 Specification; $\pm 3\%$

$$u_5 = \frac{0.03 \cdot 0.2233}{\sqrt{3}}$$

$$= 0.003868 \text{ } \mu\text{m}$$

6.3.1.2 Highest Magnification Error; 0.56%

Uncertainty of measurements; $\pm 0.08\%$ with coverage factor, $k = 2$,

$$u_6 = \frac{(0.0056 + 0.0008) \cdot 0.2233}{2}$$

$$= 0.000715 \text{ } \mu\text{m}$$

6.3.2 Rotational Accuracy in Radius Direction

6.3.2.1 Specification; $0.04 + 6H / 10000 \text{ } \mu\text{m}$,

H: measured column height in mm. In this does not measure in column, so.

$$u_7 = \frac{(0.04 + 0)/1000}{\sqrt{3}}$$

$$= 0.000349 \text{ } \mu\text{m}$$

6.3.2.2 Uncertainty of measurements; $\pm 0.1 \text{ } \mu\text{m}$ with coverage factor, $k = 2$

$$u_8 = \frac{0.1}{2}$$

$$= 0.05 \text{ } \mu\text{m}$$

Total uncertainty of this experiment is

$$\sqrt{u_A^2 + \sum_{i=1}^8 u_i^2} = \pm 0.0814 \text{ } \mu\text{m}$$

7. Conclusion

From the experiment results Michelson laser interferometer show the roundness measuring of the glass hemisphere is $0.223 \text{ } \mu\text{m}$ and the measurement uncertainty is $\pm 0.0814 \text{ } \mu\text{m}$ while the roundness of this glass hemisphere from convectional method is $0.06 \text{ } \mu\text{m}$. From the result show the difference between the purpose method and convectional method because the effect of the mechanical structure and the friction of probe movement on the accuracy of the measurement. Another effect is the difference in number of the measuring point

along hemisphere surface between two methods. There are 36 measuring points in this research.

The Experiment results show the proposed approach can be applied for roundness measurement and the roundness accuracy can be improved by take account all of the mechanical effects.

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