Non-Contact Radius Measurement Method of Spherical Standards

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Abstract. The diameter measurement of sphere is very important in dimensional metrology. The measurement of diameter is generally carried out by a comparison method or direct method using 1D linear measuring system. The probes touch both sides of the workpiece and the diameter is determined from displacement of the probes. The contact force is generally operated at 1N which yield deformation due to force of approximately 1 \( \mu \)m with uncertainty of ±0.2 \( \mu \)m. This system provides good performance but has a limitation when workpiece is made from soft matter or sensitive to scratch. National Institute of Metrology (Thailand) developed a laser interferometer system which is equipped with reference spherical lens in order to make non-contact radius measurement of spherical objects possible. Radius of completed sphere and partial sphere with radius range from 1 mm up to 50 mm can be measured with accuracy of ±2.4 \( \mu \)m.

1. Introduction

Most errors and problems on coordinate measuring machines (CMMs) are in the probe. This should be the first measuring device to check the CMM. The contact probing system of a CMM is characterized by evaluating a large number of measurements on the surface of a very precise sphere as shown in Figure 1 of known diameter. This precise sphere must be rigidly supported and held in a fixed position during the probe characterization process, otherwise misleading data will be collected.

Figure 1. Master ball.

The diameter of a circle is the length of a straight line going from one side of a circle to the opposite side. To measure the diameter, simply choose two points on the edge of a circle that are directly across
from each other, and measure the distance between these points. This method is called two-points method. There are a wide range of measuring devices which can measure diameter according to this procedure such as vernier calliper, micrometer and universal length measuring machine (ULM). Accuracy of the measurement result is highly depended on accuracy of the measuring devices and the measuring force. Wherever contact takes place, deformation will occur and lead to error in the measurement result.

As the need for more accurate measurements evolves, almost all measurements systems utilize interferometry for calibration at the highest precisions. Precision spheres have lot of metrological applications including the ball bearing industry, Gravity Probe-B experiment [1], spindle error analyzer, CMM references spheres and probe tips, Avogadro mass standard project [2] for example. Once diameter is known, one can also work forward from the diameter to find radius, circumference, volume and surface area.

The motivation for development of this instrument is to make an optical measurement system with a lowest possible uncertainty. This work is based on an instrument at NIMT which measures flatness.

2. Experimental setup
Measuring spheres has its own importance and most national labs have their own dedicated sphere measurement facility. Measurement techniques vary from one laboratory to another. While most involve combinations of diameter and roundness measurements, it is clear that uncertainty in those measurements vary considerably. The concept behind the apparatus is Fizeau interferometer between reference spherical lens and the sphere under tested. The method consists of measuring the distance between the focal point of the reference spherical lens and the confocal point between the two objects. The measurements are performed in temperature controlled environments. The reported value will be the undeformed diameter and an uncertainty budget associated with the measurement.

Key components of the measuring instrument are shown in Figure 2. In this, the sphere will be placed on the sample stage.

![Figure 2. Schematic diagram of the flatness interferometer system.](image)

Once the sphere under tested is positioned at the focal point of the reference spherical lens, the laser beam will be reflected at the surface of the sphere and return to the detector (camera) appearing as a bright spot. The returned beam will also interfere with the reference beam creating an interferogram as
shown in Figure 3. By moving the sphere under tested upward, reflected beam will disappeared. When the sphere reaches the confocal point, bright spot will reappear. The distance between the two points is equivalent to sphere’s radius.

![Figure 3](image)

**Figure 3.** Radius determination where sphere is at a) focus point and b) confocal point.

Sphere diameter range from 10 mm up to 40 mm was measured using the developed measuring system. In order to validate accuracy of the measurement result, the measurement results were compared with those obtained from the two-point method using the ULM as shown in Figure 4 which is the conventional measuring technique. This system simply consists of two in-line probe contacting the unit under-tested from opposite directions. The probing force is 1 N. Error due to deformation can be compensated through Hertzian deformation [3] via software yielding nondeformed diameter value.

![Figure 4](image)

**Figure 4.** Universal length measuring machine (ULM).

3. **Results and discussion**

Measurement results obtained from ULM and the developed system, measurement uncertainty ($U_{95\%}$) and $E_n$ values are summarized in Table 1. Measurement performed by ULM provides diameter value with uncertainty of ±0.2 μm. Whereas, measurement performed by the developed method provides radius value. Diameter is then calculated simply by multiply radius value by two.
There are many factors that contribute to the uncertainty in the measurement. Uncertainty is calculated in accordance to ‘Guide to the expression of uncertainty in measurements’ [4]. For high precision instruments, temperature is the major contributor for uncertainty. Temperature change especially in interferometry affects the measurements in two ways. Change in ambient temperature will change the dimension of the part. All these sources of uncertainty can be summarized as uncertainty involved in temperature measurement which contributes to the final value.

Table 1. Measurement results.

| Nominal value (mm) | ULM method | Developed method | En ratio |
|-------------------|------------|------------------|---------|
|                   | Value (mm) | $U_{95\%}$ ($\mu$m) | Value (mm) | $U_{95\%}$ ($\mu$m) |
| 8                 | 7.9384     | 0.2              | 7.9348   | 4.8              | 0.75       |
| 20                | 19.9994    | 0.2              | 20.0030  | 4.8              | 0.76       |
| 25                | 25.3982    | 0.2              | 25.4010  | 4.8              | 0.58       |
|                   | 25.3951    | 0.2              | 25.3913  | 4.8              | 0.81       |
|                   | 25.3931    | 0.2              | 25.3923  | 4.8              | 0.17       |
|                   | 25.3952    | 0.2              | 25.3918  | 4.8              | 0.72       |

Table 2. Uncertainty budget.

| Source of uncertainty | Standard uncertainty ($\mu$m) |
|-----------------------|-----------------------------|
| Accuracy of slider    | 0.70                        |
| Resolution of slider  | 0.54                        |
| Linearity of slider   | 0.63                        |
| Temperature measurement | 0.13                     |
| Repeatability         | 0.48                        |
| $U_{95\%}$ ($k = 2$)  | 2.4                         |

Since sphere’s radius is measured from distance between the focal point and the confocal point, the slider plays a role as a reference standard in this measurement. Whereas accuracy of laser can be neglected since it only acts as a collimated light beam. Accuracy of the slider was confirmed by comparing its length with laser interferometer. The relative uncertainty within 50 mm length is $5.50 \times 10^{-5}$. Thus, the standard uncertainty due to non-linearity of the slider is calculated to be $3.17 \times 10^{-5} L$ ($L$ is the travel length of slider). Assuming the coefficient of thermal expansion of the steel is known to 11.5 ppm/K of its value. The standard uncertainty due to temperature is calculated to be $6.64 \times 10^{-6} L$. After combining all the standard uncertainty and expanding to confident level of 95%, measurement uncertainty for sphere with radius of 12.5 mm is ±2.4 $\mu$m. Upon converting radius to diameter, measurement uncertainty of diameter value becomes ±4.8 $\mu$m.

Degree of equivalence ratio ($En$) is calculated by using Eq. (1) where $x_{ref}$ is the reference value, $x_i$ is the measured value, $U_{ref}$ is the uncertainty from the reference laboratory and $U_i$ is the measurement uncertainty of the measured value. This ratio is used to describe how two quantities are related. In case where two quantities are consistent within their measurement uncertainties, the $En$ ratio will not be more than 1. For both flick standards, the $En$ ratios are below 1 which shows a good performance of the developed probe calibration system [5].

$$En = \frac{|x_{ref} - x_i|}{\sqrt{U_{ref}^2 + U_i^2}}$$

From the result in Table 1, it is clearly shown that all measurement results are well agreed with $En$ ration below 1. It should be noted that the measurement uncertainty of the developed method is ten
times larger than the contact method. Source of uncertainty that can be reduced in order to increase accuracy of the measurement result is repeatability. As such, the detection technique in order to detect the bright spot is needed to be developed further.

4. Conclusion
The laser interferometer was developed in order to measure radius of the spherical objects. Not only a completed sphere can be measured but partial sphere can also be measured which is the key advantage of this technique. Moreover, since it is a non-contact method, deformation due to force and scratch due to contacting can be avoided. Object with radius range from 1 mm up to 50 mm can be measured with uncertainty of ±2.4 μm. This technique was evaluated by comparing the measured diameter of sphere obtained from ULM and those obtained from the developed method.

References
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