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# Development of the Probe Calibration System for the Roundness Measuring Machine

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## Abstract

The calibration system of the probing system used in roundness measuring instrument has been developed at the national institute of metrology (Thailand), NIMT. The calibration system was designed, constructed, validated and used to calibrate sensitivity and linearity of the probing system. This calibration system can help to reduce use of magnification setting standards which are need to be calibrated by the oversea national metrology institutes (NMIs) in order to retain traceability chain to the SI unit. The calibration system does not only help in reducing expense due to purchasing, maintenance and calibration of the magnification standard but also yield a measurement technology that can be transferred to the industries. The measurement uncertainty for the roundness measurement is $[9.4, 0.01 \cdot R]$ nm where $R$ is the measured roundness error of the workpiece in nm.

**Keywords :** Probe, Calibration, Roundness, Uncertainty

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## 1. Introduction

Greatest benefits to mankind have derived firstly from the invention of the alphabet and secondly from the invention of the wheel [1]. Without the later would be no technology and no civilization. Life depends on machines with rotating parts. Not only the motor car and the tools, but also the smallest watch and largest power station contain rotating parts. Many machines are making round component such as shaft, bearing, gear, bush, ball bearing and wheel.

To measure roundness, rotation is necessary. Essential features which need to be incorporated in any roundness measuring instrument are

- roundness is normally measured by rotation,
- the axis of rotation must be independent of the part being measure,
- measuring device,
- indication,
- reference datum or reference center.

Thus, main components of the roundness instrument shall consist of spindle, pick-up, amplifier, recorder and centering adjustment.

Roundness measurements are essential in mechanical production control. Each rotating part will function properly only when the correct degree of roundness is achieved according to the specification. Out of roundness can produce a number of problems, vibration, wear and noise.

In modern engineering, closer tolerances and more accurate roundness measurement are necessary. As a result, calibration of each component becomes more crucial. In the view of the fact mentioned, the evaluations of the spindle rotation errors and sensitivity of the roundness measuring instrument have become very important. Calibration standards for roundness measuring instrument can be divided into near ideal geometry embodiments, like glass-hemisphere and sensitivity standards [2-6].

There is only one type of form embodiment widely available which is applicable for the sensitivity calibration, the so-called flick standard which is a cylinder with a flat face. Nearly all roundness measuring instruments are calibrated by using a flick standard.

Previously, calibration of the roundness measuring machine at NIMT has been performed routinely using two flick standards (magnification setting standards), 19.76 μm and 273 μm, and a glass hemisphere. Glass hemisphere can be self-calibrated by using a multi-step method. However, flick standards have been calibrated by the national measurement institute of Australia (NMIA) because NIMT did not have calibration facility for flick standard with low uncertainty. This result in roundness measurement in Thailand is traceable to SI unit through NMIA. With mentioned calibration routine, roundness measurement at NIMT can be achieved with uncertainty of $Q[11.1, 0.01 \cdot R]$ nm at $k = 2$.

Many NMIs have developed calibration systems and new standard to evaluate sensitivity of the roundness measuring instrument instead of using flick standard [7-11]. Most systems are based on principle of laser interferometer due to its high resolution, high accuracy, high stability and direct traceability to the SI unit.

This paper deals with new calibration system for the sensitivity calibration. Aims of this work are to reduce calibration cost of flick standards by oversea NMIs, to increase accuracy of the roundness measurement at NIMT and to develop a calibration system that can be modified to various types of roundness measuring instrument.

## 2. Materials and methods

### 2.1 Instruments

The roundness measuring instrument used at NIMT is a Talyrond 73 manufactured by Rank Taylor Hobson as shown in Fig. 1. It has a rotating spindle with and oil-hydrostatic bearing. The spindle rotates at speed of 6 revolutions per minute. The run-out error of the spindle is roughly 40 nm. The Talyrond 73 instrument has a lever type probe with an inductive transducer (LVDT). The measuring force is approximately 50 mN.

**Fig. 1.** Roundness measuring instrument, Talyrond 73.

Stylus is made from tungsten carbide. For roundness measurement of spheres, tungsten carbide length 63.5 mm, 0.79 mm ball radius is used. While stylus with 63.5 mm effective arm length with tip protrudes 1.5 mm and hatchet radius 6.4 mm is suitable for cylinders, cones and bores. The system has 4 magnification levels corresponding to probing range as summarized in Table 1.

**Table 1** Magnification and corresponding probing range of Talyrond 73.

| Magnification | Probing range (µm) |
|---|---|
| 10x | ±625 |
| 50x | ±125 |
| 100x | ±62.5 |
| 500x | ±12.5 |

To achieve high accuracy measurement, heterodyne laser interferometer (HP 5518A) manufactured by the Hewlett-Packard was used as a reference standard. The laser interferometer system consists of a laser, a beamsplitter, a reference mirror, a corner cube and a detector. The configuration of this laser interferometer system is a Michelson type. A 1 µm resolution micrometer stage was used as a translation stage for length displacement.

Laser interferometer system and the micrometer stage were setup around the roundness measuring instrument. The corner cube was placed on the micrometer stage which fixed on the clamping stage. The clamping stage was specially designed in the way angle arm can be adjusted in both height and angular position. Two locator pins were used reference datum to adjust the parallelism between the micrometer stage's translation axis and the probing axis of the roundness measuring instrument's probe. Fig. 2 illustrated configuration of the clamping stage for probe calibration.

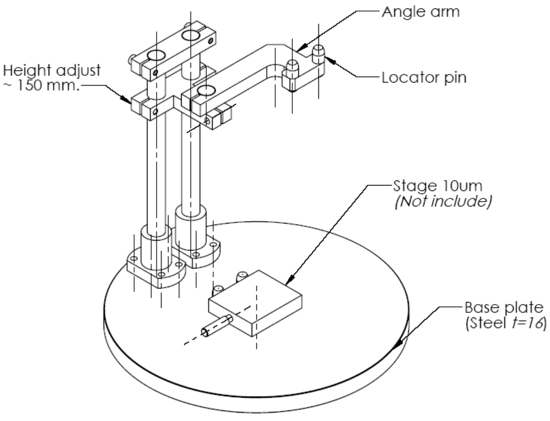

**Fig. 2.** Clamping stage for probe calibration.

### 2.2 Calibration method

Parallelism between translation axis of the micrometer stage and the datum at the locator pins is better than 2 µm at the travel length of 16 mm which is corresponding to cosine error of only 0.5 nm. The angular adjusted clamping stage was then placed on the table top of the roundness measuring instrument. Probe of the roundness measuring instrument is attached to the spindle arm which can rotate anti-clockwise only. By using two locator pins to stop the rotation movement of the spindle arm, the parallelism between axis of the roundness measuring instrument's probe and the translation axis of the micrometer stage can be fixed. After that, laser interferometer system was aligned to be inline with the translation axis of the micrometer stage. As a result, probing axis, translation axis and laser interferometer axis are all parallel to each other with parallelism better than 4 μm at the travel length of 16 mm. The measurement set-up is shown in Fig. 3.

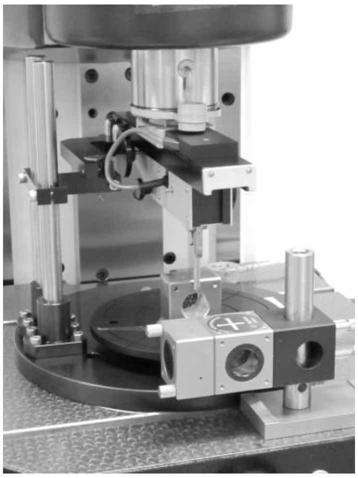

**Fig. 3.** Laser interferometer set-up on the roundness measuring instrument.

## 3. Results and discussion

The calibration of probe is carried out statically in comparison with a laser interferometer reading at varying length displacement. A micrometer stage is brought into contact with the probe, while the displacement of the stage is measured with a laser interferometer.

### 3.1 Measurement results

Due to resolution limited of the micrometer stage and alignment accuracy of the probe calibration system, probe calibration at magnification of 500x cannot be performed. Roundness measuring instrument's probe at magnification of 10x, 50x and 100x were carried out at full probing range. The measurements were repeated at least 3 times. Fig. 4 illustrates probing error obtained at magnification of 100x before and after correction.

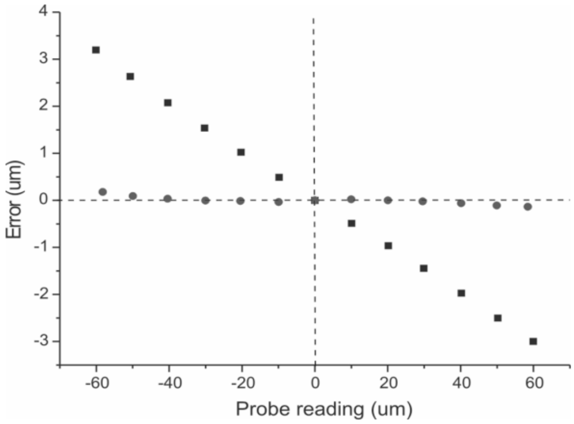

**Fig. 4.** Probe calibration results at magnification100x before correction (square) and after correction (circle).

The calibration curve can be made by plotting probe reading against laser interferometer reading. The slope of the calibration curve gives the calibration factor ($C$) as in Eq. (1) where $Z_t$ being true value and $Z_m$ being measured value. The residuals from the linear fit represent the non-linearity of the probe.

$$Z_t = C \cdot Z_m \tag{1}$$

Fig. 4 shows that the non-linearity of the ±62.5 μm range which is normally used for roundness measurement is only a few nanometers after error compensation. The linearity of the probe is important when the measured object is not perfectly centered with respect to the spindle and would show up as an apparent roundness error. After correction, non-linearity of the probe at magnification 10x, 50x and 100x not more than 0.5% of reading was obtained.

After probe calibration, flick standards size 19.76 μm and 273 μm were measured to evaluate accuracy of the probe calibration system. The measured roundness profile of flick standard size 19.76 μm is shown in Fig. 5.

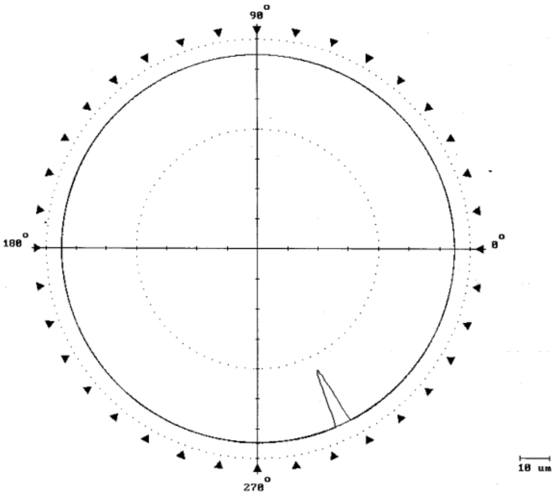

**Fig. 5.** Measured profile of flick standard size 19.76 μm.

Table 2 is the measurement results and their measurement uncertainties of both flick standards. Our measurement results were compared with reference values from NMIA to determine consistency and accuracy of the measurement results obtained from NIMT's system.

Degree of equivalence ratio (*En*) is calculated by using Eq. (2) 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.

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

**Table 2** Comparison result of flick standards measurement between NMIA and NIMT.

| Nominal value | NMIA (μm) | NIMT (μm) | En |
|---|---|---|---|
| 19.76 μm | 19.76±0.18 | 19.73±0.20 | 0.11 |
| 273 μm | 283.0±0.4 | 285.0±2.85 | 0.70 |

This ratio is used to describe how two quantities are related. In case where two quantities are consistence 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.

### 3.2 Measurement uncertainty

The measurement uncertainty was evaluated according to guideline in ISO/TS 14253-2 and "Guide to the expression of the uncertainty in measurement" (GUM) [12-13]. The uncertainties of probe calibration using laser interferometer system are summarized in Table 3. Measurement uncertainties include measurement repeatability, resolution of the laser interferometer, stability of the laser interferometer and cosine error. The combined uncertainty of 0.084 nm was obtained.

**Table 3** Uncertainty budget for probe calibration.

| Component | Quantity (nm) |
|---|---|
| Repeatability | 0.058 |
| Resolution of std. | 0.058 |
| Laser's stability | 0.005 |
| Cosine error | 0.017 |
| Combined uncertainty | 0.084 |

Components that affect roundness measurement uncertainty recommended by the ISO/TS 14253-2 are electrical noise, mechanical noise, closure error, repeatability, spindle error, magnification error, centering of workpiece and alignment of workpiece.

With the guideline above, the measurement uncertainty for roundness measurement was re-evaluated by taking into account of new combined uncertainty of probe calibration and non-linearity of probe. The measurement uncertainty of flick standard calibration at magnification of 50x is detailed in Table 4. The new measurement uncertainty at $k = 2$ is Q[9.4, 0.01·R] nm where R being measured roundness in nm. The decreasing of this new measurement uncertainty indicates an improvement in accuracy of the roundness measurement at NIMT.

**Table 4** Uncertainty budget for flick standard calibration

| Component | Quantity (nm) |
|---|---|
| Repeatability | 0.54 |
| Spindle error | 1.15 |
| Spindle calibration error | Q[4, 0.4%] |
| Probe calibration error | 0.05 |
| Probe non-linearity | 0.28% |
| Closing error | 1.73 |
| Alignment error | 1.15 |
| $U_{95\%}$ | Q[9.4, 0.01·R] |

### 3.3 Traceability

Previously, roundness measurement at NIMT is traceable to SI unit through calibration of flick standards by NMIA. The new traceability chart of roundness measurement at NIMT is illustrated in Fig. 6. Sensitivity of the roundness measuring instrument's probe is calibrated by the laser interferometer used in the developed calibration system. The spindle rotation error is determined by performing multi-step method using a glass hemisphere.

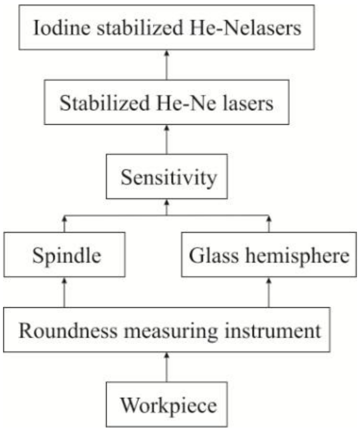

**Fig. 6.** Traceability chart for roundness measurement at NIMT.

After spindle rotation error compensations, roundness measuring instrument is capable to measure roundness deviation of workpieces such as flick standards, spheres, ring gauges, plug gauges and master balls with high accuracy.

## 4. Conclusion

The calibration system of the probing system used in roundness measuring instrument has been developed. The calibration system was designed, constructed, validated and used to calibrate sensitivity and non-linearity of the probing system of the roundness measuring instrument. The system comprises of clamping stage, micrometer stage and laser interferometer system. Such developed system is capable to determine probing error and non-linearity of the probe. The combined uncertainty of the probe calibration is 0.084 nm. As a result, the new measurement uncertainty for the roundness measurement is [9.4, 0.01·$R$] nm where $R$ is the measured roundness error of the workpiece in nm.

By using a high precision incremental length indicator such as a linear encoder or piezoelectric transformer (PZT) instead of micrometer stage, probe calibration can be performed by directly compare the probe reading with the indicator reading. It should be noted that a high precision incremental length indicator shall has accuracy at least 3 times better than the accuracy of the probing system of the roundness measuring instrument to be in accordance with ISO 10012:2003 [14].

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