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# Roundness measurement machine using multi-beam angle sensor - experimental verification of multi-beam angle sensor

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**Abstract**
In recent years it has been critical to develop both high accuracy and compact measurement machine for roundness measurement. This paper describes a high accuracy Micro Roundness Measuring Machine (Micro-RMM) using a Multi-Beam Angle Sensor (MBAS) on measuring the roundness. Compare with other methods, MBAS is less susceptible to spindle error for angle detection, and can maintain a high sensitivity with miniaturized size, which can be used as a simple and convenient one in factory-level. In this paper, the optical probe is based on the principle of autocollimator, and the stability can also be improved by using the MBAS. Unlike multi-probe methods, the Micro-RMM is constructed to realize the roundness measurement by using only one probe, which is less susceptible to instrumental errors. The experimental results confirming the feasibility of the Multi-beam angle sensor for roundness measurement are also presented.

Keywords: Autocollimator, Roundness, Calibration, Multi-Beam Angle Sensor

## 1. Introduction

In recent years, there is a growing demand for high accurate surface roundness measure techniques and for instruments which can be used to as a simple and convenient in situ, including fields such as optical metrology instruments, semiconductor industry, artificial satellite, and so on [1-2].

To measure roundness errors of cylindrical workpieces and spindle errors of machine tools in on-machine conditions, it is important to separate the roundness error and spindle error from each other. Multi-orientation method can separate the spindle error and the roundness error effectively, if the spindle error has good repeatability. Compared with multi-orientation methods, multi-probe methods are more suitable for on-machine measurements, because the repeatability of the spindle error is not necessary [3-4]. But too many sensors make it difficult to attach or remove the measured object, and it is not easy to adjust the direction of sensor's radius.

In this study, a measurement system for roundness measurement using the MBAS has been constructed. Compared to other technologies, the Micro-RMM has just used one sensor and the simple optical-path design enables the proposed setup to be insensitive to environment vibration.

## 2. Micro-RMM configuration

The configuration of the Micro-RMM includes three main parts: a Multi-Beam Angle Sensor, a rotary unit, and a bearing system. Using MBAS, we made an experimental system shown in figure 1. A cylindrical workpiece is mounted on the chuck, and the rotary platform is mounted between two XY-platforms. The axis of rotation of the workpiece spindle is represented by the Z-axis. In any roundness measuring instrument, the spindle of rotary stage is the most vitally important component in its assembly. Here, when the workpiece is assembled, it is necessary to align the Z-axis and the axis of the rotary platform to consistent with each other. The alignment is carried out by adjusting the position of two XY- platforms. Not only use the up one to achieve the minimal spindle error between workpiece and rotary stage, but also use the down one to approach almost perfect position between MBAS and rotary stage.

Fig. 2 illustrates the construction of MBAS. The laser beam passes through a pinhole and is collimated by a microlens. The beam is then bent by a beam splitter and projected through a cylindrical lens to the workpiece surface. The reflected beam from the workpiece surface passes through the beam splitter to the microlens array. After being focused on the microlens array lens, and is split into several beams. The resulting pattern is observed and recorded by a CMOS camera mounted along the vertical axis.

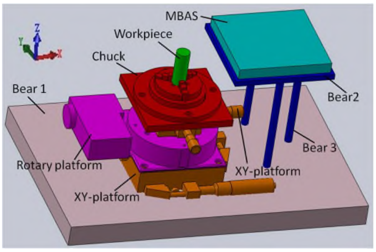



**Figure 1.** Schematic of Micro Roundness Measuring Machine

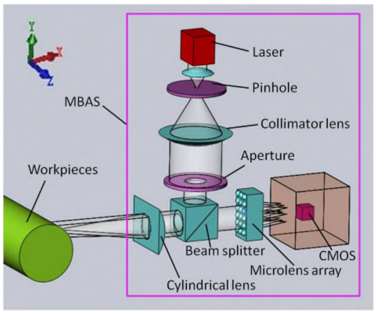



**Figure 2.** Construction of the Multi-Beam Angle Sensor

## 3. Principle of the MBAS

### *3.1. Rotary stage - less susceptible*

Figure 3 shows simulation of the reflected beam from cylindrical workpiece surface. The angle difference value Δ*c* ($c_a - c_b$) is influenced by the eccentricity of the workpiece. Though the model we can describe the Δ*c* by a simple arithmetic to be

$$c_a - c_b \approx \frac{-2o_x \sin t}{R} \tag{1}$$

The combination eliminates $o_y$, and value $o_x$ is quite small, when compared with the value *R*. Also the influence of the term ($o_x$ sin*t*) will be very small. Here curvature is the angle difference in micro area, and the curvature of workpiece can be calculated by difference of two reflected angles. Therefore, Micro-RMM can realize the roundness measurement by using the curvature, which is less susceptible to instrumental errors.

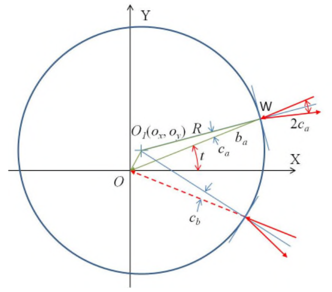



**Figure 3.** Relation between eccentricity and reflected beam
$o_x$, $o_y$: center of cylinder (eccentricity), *R*: radius of cylinder,
$c_a$, $c_b$: measured angles by MBAS, *t*: converging angle

### *3.2. Calculate the profile P*

Figure 4 shows algorithm chart of the measurement. First of all, Profile data (*P*) in the position t which is deformed by the Fourier series. Here the angle difference value (Δ*c*) can be measured by the sensor, also can be expressed as the second order differential of the profile data (*P*). Then using Fast Fourier Transformation (FFT) we can also transform the angle difference value (Δ*c*) to be the coefficient $d_i$ and $e_i$, we note that the relationship between Fourier Series ($a_i$ and $b_i$) and coefficient ($d_i$ and $e_i$). Consequently, the profile data (*P*) can be denoted as Fourier series by using Inverse fast Fourier transform.

The characteristics of the Algorithm chart can be estimated by its transfer function, which defines the relationship between the angle difference value (Δ*c*) and profile data (*P*).

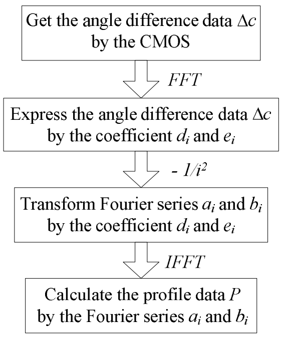


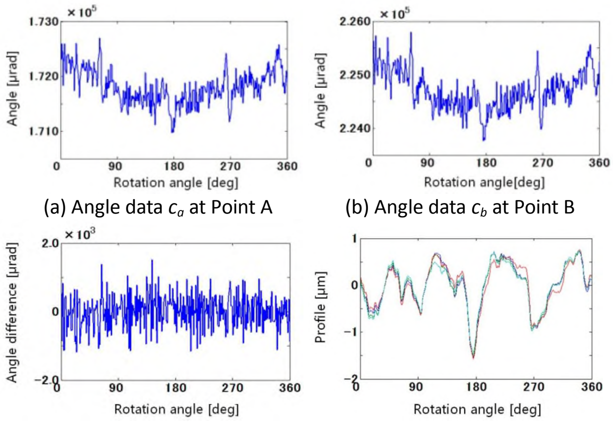

**Figure 4.** Algorithm chart of the measurement

## 4. Pre-experiment

Figure 5 shows the angle data $c_a$ and $c_b$ by MBAS system. Here, the roundness measurement of the cylinder is 2.26 µm with a repeatability of 0.027 µm.

To evaluate the developed methodology based on the MBAS method on real datasets, an experiment is developed using conventional high-precision machines (KOSAKA EC1550) for roundness assessment. Figure 6 shows the measurement roundness of two separate measurement methods. The values in the MBAS method and Radius method are 2.26 µm and 2.16 µm, respectively. It can be seen that the standard deviation is approximately 0.17 µm.

The experiment results confirm the feasibility of the Multi-beam angle sensor for roundness measurement. In the future, we still need to analyze factors influencing measurement accuracy and find measures adopted for evaluating and calibrating of the Multi-beam angle sensor.




(a) Angle data $c_a$ at Point A (b) Angle data $c_b$ at Point B

(c) Angle difference data Δc (d) Profile data (four times)

**Figure 5.** Measured results by MBAS

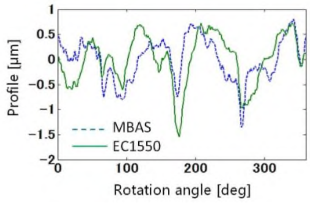



**Figure 6.** Compare with the Radius method

## 5. Conclusions

A high accuracy Micro Roundness Measuring Machine (Micro-RMM) using a Multi-Beam Angle Sensor for roundness measurement has been constructed. Comparing with other methods, MBAS is less susceptible to instrumental errors for angle detection, and can maintain a high sensitivity with miniaturized size. The resolution of MBAS is 0.05 µrad. The optical probe is based on the principle of autocollimator and has a stability of 2.35 µrad. The roundness measurement of the cylinder is 2.26 µm with a repeatability of 0.027 µm. The experimental results confirming the feasibility of the MBAS for roundness measurement are also presented.

In the future, we will calibrate the sensor, and a new experiment has been designed. We are planning to do uncertainty analysis for the roundness measurements in the near future and do the improvement.

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