Development of Highly Accurate and Robust Roundness Measuring Instrument

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Abstract. We developed a high accuracy roundness measuring instrument with high robustness. The high robustness is achieved by utilizing contactless mechanisms for two moving axes. Air bearing technique is used as guiding mechanism and linear shaft motor technique is used as driving mechanism. We discuss several key techniques to achieve the highly accurate and robust roundness measurements. In regard to achieved accuracy parameters, the key feature is the parallelism error to be within 0.5 μm/350mm.

1. Introduction

Recently we are facing increasing demands for higher accuracy in roundness measurement. The demand is mainly driven by the automotive industry. High demand for improved fuel efficiency is the key driving force for the high-accuracy roundness measurements. For example, the fuel injection module is needed to be manufactured precisely in order to obtain the designed ignition in diesel engines. In addition, especially in developed countries, we are confronting strong demands for labor savings. To address the problem, the roundness measurement instrument is needed to be as maintenance-free as possible, keeping its high accuracy. Thus, a highly accurate and robust roundness measuring instrument is wanted.

Research institutes also require high accuracy roundness measurement, in order to fulfill the demands described above. Again, the robustness is the important feature to keep its high accuracy whenever it is required.

Thus, we decided to develop a highly accurate and robust roundness measurement instrument. Requirements for the new roundness measuring instrument are as follows;

- High accuracy roundness measurement
- High robustness
- Low vibration for roughness measurements

The section 2 describes components of the developed roundness measuring instrument, focusing several key features in its design. The obtained results are described in the section 3, and we summarize the development in the section 4.

2. Apparatus

2.1.1. Outline

Figure 1 shows the overview of developed roundness measuring instrument components. It is consisted of following components; the base, the rotational air bearing, the alignment table, the column, the carriage, the arm, and the detector. The workpiece is placed on the alignment table. The alignment table is fixed to the rotational air bearing, and the air bearing produces the highly accurate rotational movement. The column is a vertical structure, guiding the movement of the carriage. The carriage holds horizontal movement structure, called the arm. While rotating the workpiece, the deviation of surface position is detected by a detector. The detector is attached to the end of the arm.
2.1.2. **Base**

The base holds the rotational air bearing and the column. Deformation of the base causes a change in parallelism between the rotational axis of air bearing, and the vertical guide of column. Thus it causes the deterioration in cylindricity measurement accuracy.

Such a deformation is mainly caused by two reasons: temperature change and weight load of the workpiece. To reduce the effect of temperature change, the base is made of the same material (cast iron) as the support structure of air bearing and the column. To reduce the effect of workpiece weight, the support legs of the base are located at the position of rotational air bearing axis. We employed a finite element method (FEM) simulation for this design, and as shown in Fig. 2, we achieved a great improvement when we positioned support legs at the axis of rotational air bearing.

![Fig. 1 Schematic drawing of the roundness measuring instrument](image)

2.1.3. **Rotational Air Bearing**

A rotational air bearing is the key component to achieve high accuracy roundness measurements. Also, it is important to reduce the vibration caused by the air bearing, in order to realize a high precision roughness measurement. We developed a new orifice for aerostatic air bearing, and fulfilled the low vibration requirement.

2.1.4. **Column (Vertical Axis) and Arm (Horizontal Axis)**

The column is a vertical structure, and acts as a guide for the carriage. The arm is held by the carriage and moves horizontally. The surface of the arm works as a guide for horizontal movement of the arm. Both movement is guided by aerostatic air bearing, and is driven by linear shaft motors. The both mechanisms of air bearing guides and linear motor drive are contactless, and thus there is no frictional wearing. With this feature, the roundness measuring instrument has high robustness.

Also the structural shape of the column is important to guide the carriage in a straight line. The column is pushed by air bearing pads that guides the carriage movement, and the force of air bearing pads causes column deformation. Figure 3 shows the difference between a column with ribbed
structure and with a structure without rib. We see the ribbed structure may cause waving deformation depending on the vertical position of carriage, whereas the structure without ribs has a simple shaped deformation. We employ straightness corrections according to this deformation, and it is much easier to correct the simple shaped deformation. Thus, we selected the structure without ribs for the column.

![Cross Sectional View](image1.png)  
![Cross Sectional View](image2.png)

Fig. 3 (color online) The top left (top right) figure shows the column structure with (without) ribs, respectively. Estimated deformation of column that is caused by air pads are shown in bottom left (bottom right) figures for the case with (without) rib structures, respectively.

### 3. Experimental Results

The developed instrument is experimentally evaluated by many measurements for several months in repeatability and in reproducibility using our reference standards. The authors estimated the accuracy of the developed instrument as shown in Table 1.

| Units         | Items                  | Specifications                             | Remarks     |
|---------------|------------------------|-------------------------------------------|-------------|
| Air Bearing   | Rotation Accuracy (Radial) | [0.01+3H/10000] μm                         | H is the height in [mm] |
| (Rotational)  | Rotation Accuracy (Axial) | [0.02+3R/10,000] μm                        | R is the radius in [mm] |
| Column        | Straightness Accuracy  | 0.13μm/350mm, 0.05μm/100mm                |             |
| (Vertical)    | Parallelism (Z/T axis)  | 0.5 μm / 350mm                            | 20 ± 1.0°C  |
|               | Vibration               | 20nm Ra                                    |             |
| Arm           | Straightness Accuracy  | 0.2μm / 200mm                              |             |
| (Horizontal)  | Parallelism (R/T axis)  | 0.3μm / 200mm                              |             |
|               | Vibration               | 20nm Ra                                    |             |
3.1.1. Roundness Accuracy  
Roundness accuracy is determined by a roundness accuracy separating technique. The technique is a method that we measure a master ball multiple times by changing the rotational position of master ball. With this method, roundness deviation of master ball and rotational air bearing can be separated, and be calculated independently [1]. We utilized the method to estimate the roundness accuracy of the instrument’s air bearing.

3.1.2. Temperature Dependence of Parallelism Accuracy  
Accuracy of parallelism is mainly dependent on the temperature fluctuation. We carried out continuous parallelism measurements of the cylindrical master workpiece, and changed the room temperature. The temperature was changed between 19°C and 21°C. The temperature controlling accuracy of the room was less than 0.1 °C. Figure 4 shows the deviation of parallelism accuracy by changing the room temperature. We achieved the parallelism accuracy of 0.5 μm in the temperature range of 20 ± 1 °C.

Though, if you need to control the room temperature to be within ±1 °C, you may need a specially air conditioned inspection room. In order to obtain the high accuracy at “normally” air conditioned room, we tried to add a small air conditioning unit in order to mitigate the ambient temperature fluctuation. As shown in Fig. 4, we succeeded to achieve the same parallelism accuracy, even if the room temperature is changed from 18 °C to 22 °C.

![Fig. 4 Temperature dependence of parallelism accuracy. Left figure shows the case without the air conditioning unit and the right shows the case with air conditioning unit.](image)

4. Conclusion  
We developed a high accuracy roundness measuring instrument with high robustness. To achieve the high accuracy, we optimized the mechanical structure of the base and column. In order to achieve the high robustness, we used contactless mechanism for two moving axis, both guiding and driving mechanism. According to the design described above, we succeeded to achieve the high accuracy and high robustness. We also experimentally measured the temperature dependence of parallelism, and we obtained that the instrument keeps its parallelism error to be within 0.5μm / 350mm, if the temperature is in 20 ± 1 °C.

References  
[1] Evans, et. al. 1996. Self-calibration: reversal, redundancy, error separation, and “absolute testing”. Annals of the CIRP, v.45/2.