

FORM ERROR MEASUREMENT BY COMPARISON WITH A REFERENCE OBJECT

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Traditionally, form error measuring machines compares the form of the object with a precise linear or rotary motion generated by a precision bearing. As an alternative strategy, this paper presents a strategy based on the comparison of the object form with the form of a second object. This makes the measurement accuracy independent of the motion accuracy of the measuring machine, opening possibilities for keeping conventional measurement accuracy but using bearings of lower accuracy – this means measuring machines of lower cost. A roundness measuring system based on this new strategy is presented. Even using a ball-bearing with non-repetitive motion errors larger than $2\mu\text{m}$, the presented system, shows a final measurement repeatability better than $0.3\mu\text{m}$, proving the effectiveness of the proposed strategy.

Keywords: *form measurement, roundness measurement, error separation technique*

1. Introduction

In conventional measuring machines such as roundness measuring machine (RMM) or straightness measuring machine (SMM), the measurement accuracy is affected by repetitive and non-repetitive motion errors of the measuring machine. Therefore, in such machines, high measurement accuracy is assured by using precision bearings (oil-film and air-film bearings) and isolating the machine from external disturbance sources.

In recent years, a sort of techniques was developed to compensate systematic measurement error caused by motion errors present in the measuring machine. The motion error is previously measured by comparing it to an external datum and then, the measurement result is compensated. The external datum can be a masterpiece like a straight edge or a master sphere. However this strategy is effective only to reduce systematic measurement errors.

Therefore, this work identifies a strategy to compensate measurement errors of both, repetitive and non-repetitive, nature induced by motion errors. While in the conventional strategies, the form of the object is compared to a motion, in the present strategy, the form of the object is measured by comparing it to the form of a second object, i.e. an auxiliary reference. This strategy is referred here as FFC, Form – Form Comparison, strategy.

Some measurement methods follow FFC strategy, making the measuring accuracy independent of the motion accuracy of the bearing. In the multi point method^{1,2)}, the influences of motion errors are removed from sensor readings by measuring the object simultaneously by two or more sensors. An another method consists on the direct comparison of the object with a masterpiece such as a master sphere³⁾. However these methods has some problems. The multi point method has the problem of different gain for each harmonic existent in the form of the object. The direct comparison with a masterpiece has a serious practical problem on maintaining the original profile of the masterpiece. The profile of a masterpiece may change when fixed to the machine or suffers some damages. At least in the case of roundness measurement, the problems are minimized by the Improved Reversal Method – IRM⁴⁾, described later.

In order to demonstrate the effectiveness of the FFC strategy, this work presents an example of a roundness measurement system that was designed according to the strategy and uses the IRM to measure the roundness of objects.

2. The Improved Reversal Method –IRM⁴⁾

In the IRM, the object is firstly set on a second round object, which works as an auxiliary reference (see Fig.1(a)). Then, both objects are rotated and measured simultaneously resulting in the following sensor readings:

$$s_1(\theta) = h(\theta) + t(\theta) \quad (1)$$

$$s_2(\theta) = q(\theta) + t(\theta) \quad (2)$$

Where, θ is the angular position, $s_1(\theta)$ is the reading of sensor 1, $s_2(\theta)$ is the reading of sensor 2, $h(\theta)$ is the object roundness, $q(\theta)$ is the roundness of the auxiliary reference and $t(\theta)$ is the radial motion error of the table.

In the next step, the object is reverted with respect to the auxiliary reference and the sensor installed in the opposite side (Fig.1(b)). Then, both elements are rotated and measured again resulting in the following sensor readings:

$$s'_1(\theta) = h(\theta) + t'(\theta) \quad (3)$$

$$s'_2(\theta) = q(\theta) - t'(\theta) \quad (4)$$

$s'_1(\theta)$ and $s'_2(\theta)$ are new readings respectively of the sensors 1 and 2. $t'(\theta)$ is the motion error during the 2nd measurement executed after the reversion. $t'(\theta)$ is not necessarily equal to the motion error $t(\theta)$.

Finally, using all sensor readings (Eqs.(1)~(4)), the roundness is obtained as follows.

$$h(\theta) = [(s_1(\theta) - s_2(\theta)) + (s'_1(\theta) + s'_2(\theta))] / 2 \quad (5)$$

The operations $(s_1(\theta) - s_2(\theta))$ and $(s'_1(\theta) + s'_2(\theta))$ executed in Eq.(5) represent a comparison between the profile of the object and of the auxiliary reference. Therefore, the IRM follows the proposal of this work, i.e. the comparison between forms.

3. The prototype

According to the FFC strategy and assuming the use of the IRM, a prototype of a roundness measuring system is developed (Fig.2). Similar to a conventional RMM, the system consists of a rotary table, displacement sensors and a computer system. The most significant difference with respect to a conventional RMM is related to the motion accuracy of the table. Instead of a high accuracy bearing, this system uses ball bearings. The use of a ball bearing is particularly interesting since it ensures reasonable motion accuracy (on the order of μm), is robust, is easily maintainable and is largely available in the market. A lathe finished table of $\phi 150\text{mm}$ of diameter is fixed to a shaft and the shaft is suspended by a pair of ball bearings (NSK/6305Z, radial run-out less than $1\mu\text{m}$). The shaft is equipped in its lower extremity with an encoder that generates 256 pulses/rev and an origin reference pulse. By using these pulses for synchronization, signals from two non-contact capacitive gap sensors (ADE3800, gain: $0.4\text{V}/\mu\text{m}$, resolution $0.05\mu\text{m}$) are

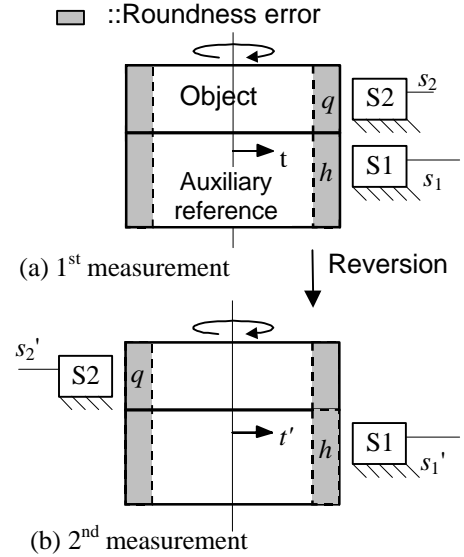


Figure 1 The IRM

sampled and stored in the computer. During experiments, the table is rotated manually at a speed of approximately 5rpm.

4. Results

Readings of the sensor 1 and 2 are sampled simultaneously during 20 successive rotations. Figure 3 shows readings of the sensor 2. It indicates the presence of non-repetitive motion errors with a peak-to-peak value of approximately $2\mu\text{m}$. These errors are mainly consequence of the clearance in the ball bearings. If the equipment presented in Fig.2 is used as a RMM, the reading of sensor 2 is used directly as the object roundness. Even assuming that the table does not have repetitive motion errors, non-repetitive errors limit the measurement accuracy to $2\mu\text{m}$.

After sampling, sensor readings are processed according with the IRM (Eq.(5)) using sensor readings collected along 20 successive rotations, before and after the reversion. Results are shown in Fig.4. The peak-to-peak value of the measurement repeatability is about $0.3\mu\text{m}$, which is almost 10 times better than the direct measurement (Fig.3). The largest standard deviation (σ) along 20 measurements is $0.084\mu\text{m}$. These results, show that a measurement accuracy superior to that of the motion accuracy is obtained by the IRM, showing the effectiveness of the FFC (Form-Form Comparison) strategy.

Although it is not a relevant result in practical applications, the IRM can isolate motion error of the table during the measurement. The motion errors before the reversion are presented in Fig.5. Similar motion errors are observed after the reversion, suggesting the presence of motion error components of repetitive nature. The repeatability of the motion error in terms of peak-to-peak value is close to $2\mu\text{m}$.

Repetitive motion errors can be eliminated from sensor readings by using the Reversal Method – RM⁵⁾. Using the same readings of sensor 2 that are used in Figs.4 and 5, 20 object roundness are obtained using the RM. The results are shown in Fig.6. These results are very similar to those obtained using the IRM (Fig.4), suggesting the validation of the measurements executed by the IRM. A lower repeatability, larger than $1\mu\text{m}$, is observed in the case of the RM because of non-repetitive motion errors present in the measuring machine.

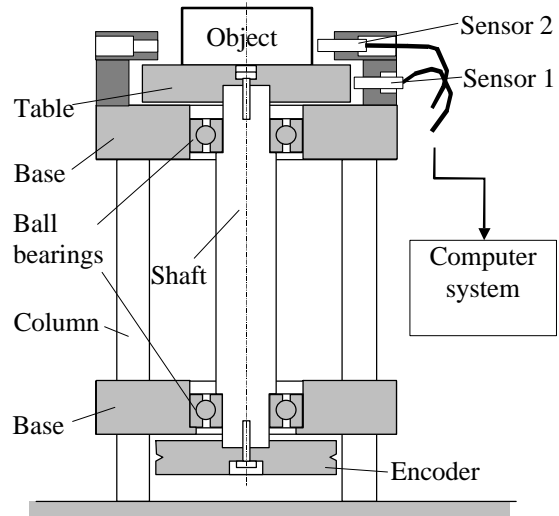


Figure 2 The prototype

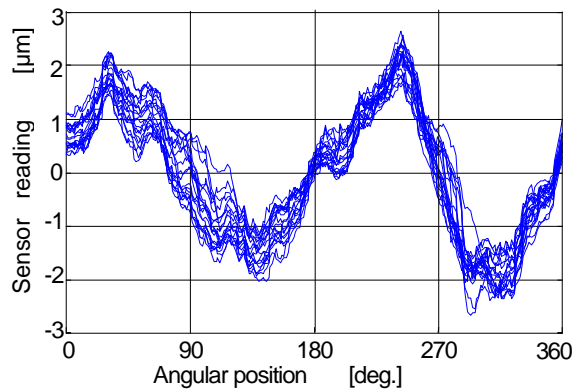


Figure 3 The readings of sensor 2.

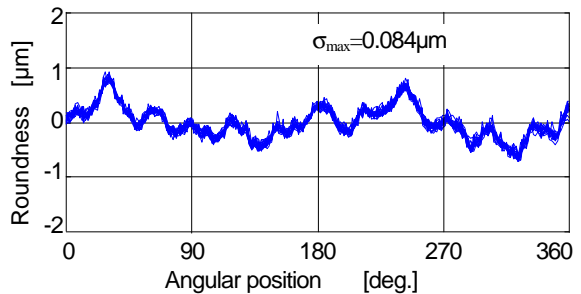


Figure 4 The roundness.

In Fig.7, the measurement by the IRM is compared to that obtained by a conventional RMM (Taylor-Hobson, Talyrond 200). The maximum deviation between results is around $0.2\mu\text{m}$. The deviation is explained by the difference in the sensor used in the measurement. The IRM uses non-contact sensor with a circular sensitive area of approximately 5mm diameter, while the RMM uses a stylus type contact sensor. Despite the deviation, the measurement by the IRM is in good conformity with that obtained by the RMM.

5. Conclusions

This work presented a form measuring strategy that is based on the comparison of the form of the object with the form of a second object. By the strategy, the measuring accuracy becomes independent of the repetitive and non-repetitive motion errors of the motion mechanism used in the measurement. As consequence, the present strategy opens possibilities for developing measuring machines with accuracy similar to the traditional ones but of lower cost because of the use of bearing of lower accuracy. This is the most interesting aspect of this strategy.

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8. References

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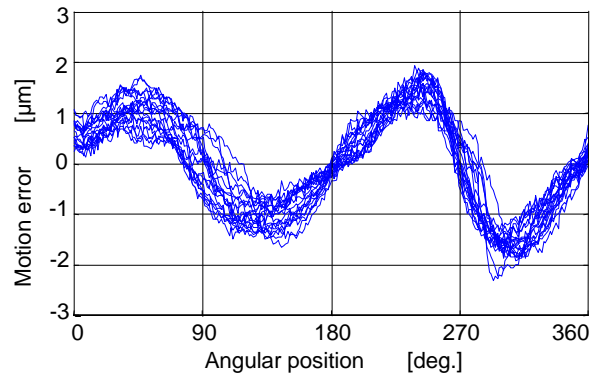


Figure 5 Motion errors.

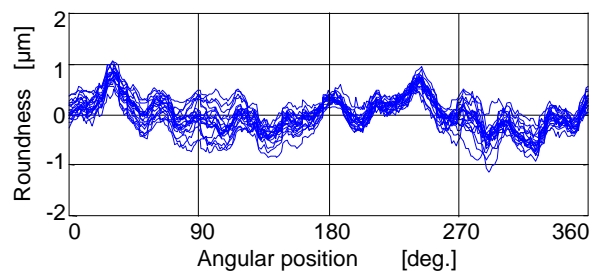


Figure 6 Measurements using the RM.

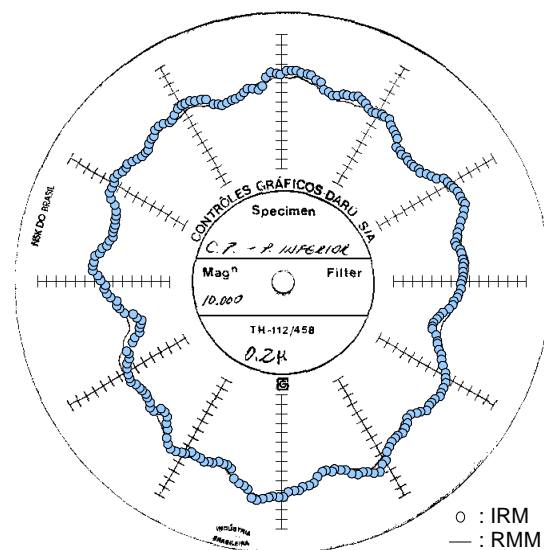


Figure 7 Measurement by a RMM.