

# Precision angle comparator using self-calibration of scale errors based on the equal-division-averaged method

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## Abstract

An angle comparator for precision angle measurement is presented, which used the equal-division-averaged (EDA) method to self-calibrate the scale errors of a divided circle. The angle comparator mainly consists of an air bearing, friction motors, and a self-calibratable angle encoder. Using the air bearing and friction motors, we can generate the angular position with the resolution of less than 0.005". The divided circle of the angle encoder has 64800 signal periods within 360° and the final reading resolution is about 0.005". Through the self-calibration procedure based on the EDA method, the scale error can be effectively compensated.

## 1 Introduction

Angle measurement has a key role in various precision engineering, and many artefacts and instruments are used for angle metrology, such as angle gauge blocks, optical polygons, and rotary tables [1,2]. To ensure high reliability, these should be calibrated using standard instruments such as an indexing table and an autocollimator. However, the indexing table has limited resolution and manual operation, and a small angle generator is only applied to the calibration of an autocollimator because of limited measurement range. Therefore, some NMIs (National Measurement Institutes) developed angle comparators to generate very fine and accurate angular position within the full circle range [3,4]. They consist of an actuating part to generate angular motion, a precision angle encoder to measure angular position, and a controller. The scale error of a divided circle was compensated with several methods [5-7]. In this paper, we present a precision angle comparator which uses the EDA method [5] to reduce the scale error of the divided circle. Using the outputs of multiple encoder sensors, the scale error can be compensated effectively. The configuration of the angle comparator and the self-calibration procedure are explained. The calibration curve was obtained experimentally and analyzed.

## 2 Configuration of the angle comparator

The angle comparator consists of a cylindrical air bearing, ultrasonic motors, a precision angle encoder, and a controller (figure 1 (a)). The air bearing precisely guides the angular motion of the angle comparator, which is generated by the eight ultrasonic motors. We coated a ceramic strip on the bottom side of a rotating plate. This configuration can obtain high resolution and unlimited rotating range without addition reduction mechanism. The motors were placed circularly on the bearing stator with equal spacing and a motor driver switches an operation mode to achieve fine resolution within the full circle range. A divided circle and twelve encoder heads compose the precision angle encoder. The divided circle has 64 800 lines (signal period: 20"). It is fixed on the bottom side of the bearing rotor and its angular position is read with the encoder head. The sinusoidal outputs of the encoder head are processed in a signal processing module, and the final readout has the resolution of about 0.005". The specifications of main components of the angle generator are summarized in Table 1.

Table 1: Specifications of main components of the angle comparator.

Component	Model (Manufacturer)	Specification
Cylindrical air bearing	Model 10R (Professional Instruments Company)	Radial stiffness: 350 N/μm Axial stiffness: 1750 N/μm Run-out: 0.03 μm
Ultrasonic motor	HR2 (Nanomotion)	Resolution: ≤ 0.005" (in DC mode) Maximum speed: ~30 rpm (in AC mode)
Ultrasonic motor driver	AB2 (Nanomotion)	Driving modes: AC, Step, DC
Encoder head	M10 (MicroE Systems)	Output: sinusoidal wave (1 V <sub>pp</sub> )
Signal processing module	SS-350Si (MicroE Systems)	Resolution: ~0.005"

To apply the EDA method, the twelve encoder heads were placed as shown in figure 1 (b). They were grouped in two arrangement sets dividing the full circle equally by 6 and 7. Using the averaged readout of each set, we can obtain the complete scale error spectrum except  $6 \times 7 \times n$  ( $n = 1, 2 \dots$ ) and compensate the scale error of the divided circle effectively.

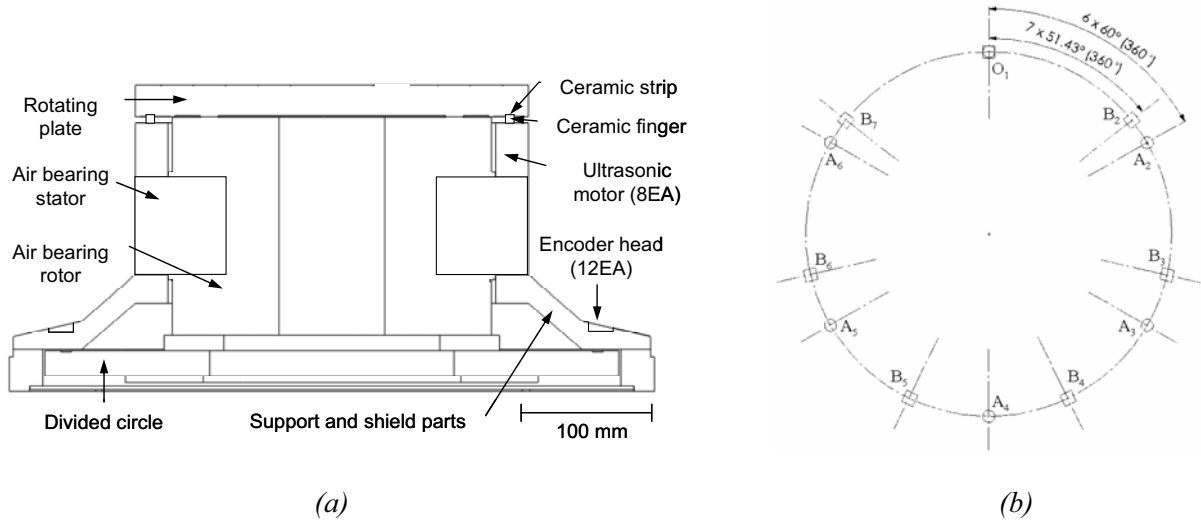


Figure 1: (a) Configuration of the angle comparator; (b) Arrangement of the twelve encoder heads for the EDA method.

The final readout ( $\theta$ ) of the angle comparator is calculated as the mean value of the averaged readout of the two arrangement sets as equation (1).

$$\theta = \frac{1}{2} \times \left( \frac{O_1 + \sum_{i=2}^6 A_i}{6} + \frac{O_1 + \sum_{i=2}^7 B_i}{7} \right) = \frac{1}{84} \times \left( 13 \times O_1 + 7 \times \sum_{i=2}^6 A_i + 6 \times \sum_{i=2}^7 B_i \right), \quad (1)$$

where  $O_1$  is the readout of the encoder head which is commonly used in both arrangement sets. The  $A_i$  and  $B_i$  are the readouts of the encoder sets dividing the full circle by 6 and 7, respectively.

### 3 Scale error calibration

The self-calibration procedure using the EDA method was implemented as follows. Firstly, we acquired the outputs of every encoder head within one revolution (0.64" intervals). Through the FFT analysis, the reference data was calculated from the averages of 6 and 7 encoder sets. The deviation between the reference data and the output of each encoder head was assigned as the compensation value. The final compensation data was obtained by averaging the compensation value of each encoder head through similar way shown in equation (1). The short term repeatability of the averaged compensation data was less than 0.002", which was evaluated in three times repeated calibration for nine hours.

Figure 2 (a) shows the compensation curve of one encoder head where the eccentricity error caused by the misalignment of the divided circle was not included to represent inherent scale error of the divided circle. The magnitude of the scale error was about  $\pm 0.4$ ". In the FFT spectrum of the scale error, the scale errors were reduced as the mode number increased, but they decreased rather slowly and several peaks were found in some high order modes (figure 2 (b)).

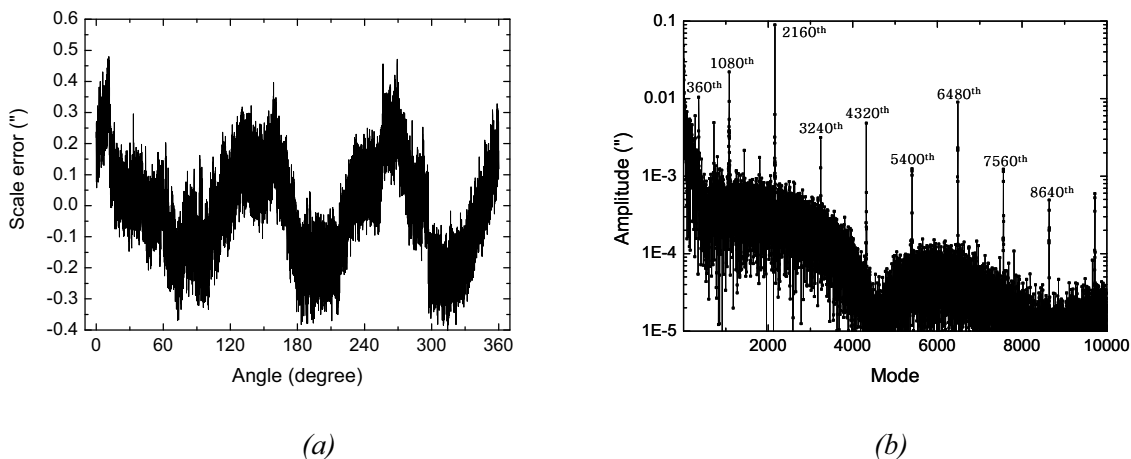


Figure 2: (a) Compensation curve of one encoder head; (b) FFT spectrum of the scale error.

These results seem to be related to the detector width of the encoder head and the pitch of the divided circle, which are 600  $\mu\text{m}$  and 20  $\mu\text{m}$ , respectively. The encoder head having the limited detector width can not average out the high order terms sufficiently. The detector width which is multiple of the scale pitch amplified the scale error at specific modes such as the 2160<sup>th</sup> mode, and several harmonics terms were also generated. In theory, these terms can be compensated using the averaged output of seven encoder heads because they are not multiples of 7. However, because of non-uniformity and non-ideal angular positions of the multiple encoder heads, these terms could not be compensated completely, especially for higher order terms. To evaluate the performance of the angle comparator, we investigated the calibration results of a precision angle encoder and an autocollimator. Its accuracy was also estimated through an uncertainty evaluation, and the main uncertainty sources were the nonlinearity error and the stability of calibrated scale error [8].

### 4 Conclusion

We developed an angle comparator for precision angle metrology. It can generate fine angular motion with 0.005" resolution within the full circle range using the ultrasonic motors, and compensate the

scale error of the divided circle using the self-calibration method. The EDA method was implemented easily with multiple readouts of encoder heads. However, the effectiveness of the EDA method was reduced by several factors: the limited detector width, non-uniformity and non-ideal angular positions of the multiple encoders. The expanded uncertainty ( $k = 2$ ) of the angle comparator was estimated as less than  $0.05''$  through the performance evaluation using a precision angle encoder and an autocollimator.

## Acknowledgement

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