

## HIGH ACCURACY ANGLE INDEXING TABLE

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**Abstract:** National Metrology Institute of Japan studied the high precision angle indexing table. We used the principle that NPL reported the indexing accuracy 0.01 " in 1984 [1]. We verified this principle using the angular primary standard of Japan and proved this principle can exceed 0.001 " super-high angular precision.

**Keywords:** angle, indexing table, standard.

### 1. INTRODUCTION

Angle measuring instruments such as a rotary encoder, autocollimator and an angle interferometer are progressing in both sides of high accuracy and high resolution, that accuracy becomes 0.1 " and the resolution shows 0.001 " by using electric interpolator. In order to use these angle measuring instruments in comfort, the accuracy estimation under the traceability system which has reliability is required, therefore National Metrology Institute of Japan (NMIJ) developed the rotary encoder self-calibration system used the Masuda-Kajitani method and established the angular traceability system in Japan. This equipment can calibrate the digital signal of all the scales of a rotary encoder (limit is 300,000 graduation lines) and the uncertainty is an about 0.01 " that is the highest level in the world. However, the calibration resolution is about 5 " that is not sufficient against 0.001 " resolution of angular instruments.

NMIJ is developing the super high precision angle indexing table by using the principle that an angle is the 360° closure circle system. This principle were developed by Štěpánek in 1958 [2], and NPL (National Physical Laboratory, United Kingdom) and PTB (Physikalisch-Technische Bundesanstalt, Germany) have already carried out the experimental verification [1,3]. They had successful experiment results of angle indexing in the accuracy of 0.01" which is the highest accuracy performance at that time. However, by development of the latest processing technology such as air bearing, we have a possibility to attain the development of a super-high accuracy angle indexing table.

In this research, we introduce the outline of the principle of this method and the performance of our research set up for this principle.

### 2. PRINCIPLE

In Fig. 1, the left side figure shows the conceptual setup of the principle of this instrument and the left side figure shows the angle calibration system of the NMIJ which is the primary standard of an angle. A basic principle is that an analysis of the difference of the angle outputs from two rotary encoders that their scale disks of two rotary encoders are connected with the same axle. The reading head of the rotary encoder B is fixed to the base body and the reading head of the rotary encoder A is fixed to the axis of a upside

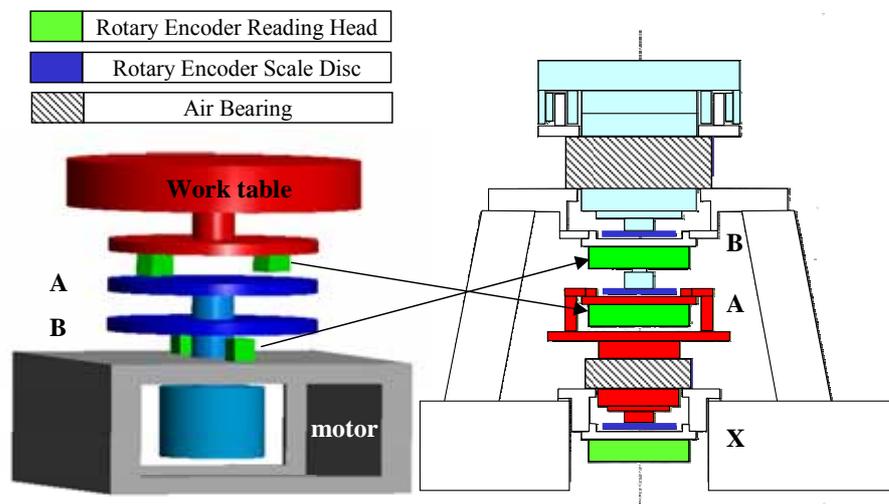


Fig. 1. The principle set-up

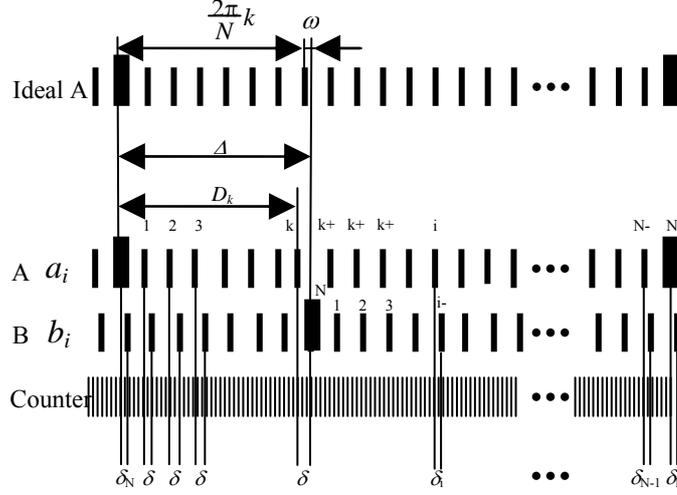


Fig. 2. Angular signal relation between rotary encoder A and B

worktable that can be indexed in the arbitrary angle positions around  $360^\circ$ . Fig. 2 shows the time relation of out coming signal  $a_i$  and  $b_i$  from encoder A and B respectively, where  $i$  is graduation line number and  $N$  is total number of graduation line. Bold lines show the first signal after index line of encoder. The signal  $a_i$  and  $b_i$  are obtained by following formula,

$$\begin{aligned} a_i &= \frac{2\pi}{N}i + \alpha_i, \\ b_i &= \frac{2\pi}{N}i + \beta_i \end{aligned} \quad (1)$$

where  $a_i$  and  $b_i$  are constituted by value  $2\pi i/N$  which divided  $360^\circ$  into the ideal equal angle interval, and  $\alpha_i$  and  $\beta_i$  which are synthesized with the graduation position deviation from the ideal angle graduation position and eccentricity error. When we control the worktable that has a difference of indexed position angle  $\Delta$  as shown in fig.2, the most simple equation for evaluate the  $\Delta$  value is  $\Delta = D_k + \delta_k$ , where  $k$  is a number of signals of encoder A between both index lines of encoder A and B,  $\delta_i$  is an angle deviation between  $a_i$  and  $b_{i-k}$  in this set up in fig. 2. However it is not easy to estimate  $D_k$  value from  $a_k$ , because  $a_k$  includes unknown graduation line position error  $\alpha_k$ . Therefore we have to have another approach to estimate  $\Delta$  value, and we use following formula,

$$\Delta = \frac{2\pi}{N}k + \omega, \quad (2)$$

where  $\omega$  is the angle deviation between ideal encoder A and  $b_N$  in this setup of fig.2, in other words, the angle deviation between ideal encoder A and ideal encoder B. Here, by using  $\omega$  we can represent  $\delta_i$  value in different notation,

$$\begin{aligned} \delta_i &= b_{k-i} - a_i \\ &= \omega + \beta_{k-i} - \alpha_i \end{aligned} \quad (3)$$

When we want know  $\omega$  value, we evaluate it from the mean value of  $\delta_i$  over all  $360^\circ$  as shown in eq. (4),

$$\begin{aligned} \frac{1}{N} \sum_{i=1}^N \delta_i &= \omega + \frac{1}{N} \sum_{i=1}^N \beta_{k-i} + \frac{1}{N} \sum_{i=1}^N \alpha_i \\ &= \omega, \end{aligned} \quad (4)$$

$$\begin{aligned} \sum_{i=1}^N \alpha_i &= 0, \\ \sum_{i=1}^N \beta_{k-i} &= \sum_{i=1}^N \beta_i = 0 \end{aligned} \quad (5)$$

there, the sum of each  $\alpha_i$  and  $\beta_i$  become 0 because of the graduation line return to index position, that is, the principle of  $360^\circ$  angle closure circle system. Therefore, when the difference of  $a_i$  and  $b_i$  is averaged over one revolution, even if it takes into consideration neither a scale error nor an eccentricity error, the difference  $\omega$  of the angle of the head position of the exact rotary encoders A and B can be determined.

Fig.3 shows the calibration data of both rotary encoder A and B, therefore when adding the eccentricity error, these value become  $\alpha_i$  and  $\beta_i$ .

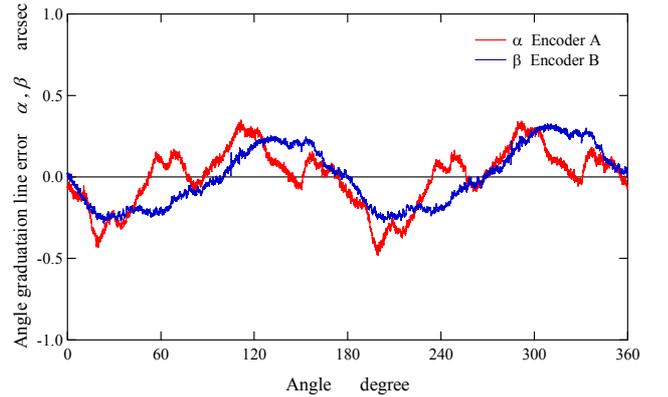


Fig. 3. Calibration data of rotary encoder A and B

### 3. EXPERIMENT AND RESULT

Experiment system is shown in the right figure of Fig. 1. This system has structure which arranges to be upside-down of the rotary encoders' position against a principle figure shown in the left of Fig. 1. The built in rotary encoders A, B and X have the same number of 225000 graduation lines

manufactured by Canon Inc. (X-1M), so angle pitch interval becomes 5.76". The reading head of the encoder A can be controlled using the servo-control by the bottom encoder X which used the electric interpolator of 2048 times division number, therefore the indexing angle resolution is 0.0028". The servo-control stability is about  $\pm 4$  pulses. The revolution speed of graduation disks are 5 rpm. The external counter clock is a quartz oscillator of 50 MHz, the measuring resolution is about 0.002" in the case of 5 rpm.

Fig. 4 shows the data of angle deviation  $\delta_i$  with collection value  $2\pi/N$  as shown in eq.(2) at the indexing position of worktable (start position, 1", 4", 8" and 16") and each mean value correspond to the  $2\pi k/N + \omega$ . Indexing position of reading head A is controlled by bottom encoder X. The rotary encoder X also has angle position error from ideal position. This error of the encoder X makes small difference (1.0280-1", 4.0810-4", 8.0852-8" and 16.1224-16") from the indexing position indicated by encoder X for worktable angle position. However the exact indexing angle is determined by using eqs. (2), (4).

Fig. 5 shows the result of repeatability of the indexing position. Since the revolution speed is 5 rpm so that one revolution takes time of 12 seconds for determining the indexing position and we measured total 112 revolution times at the same position. Therefore, the repeatability measurement in Fig.5 takes about 22 minutes. From this

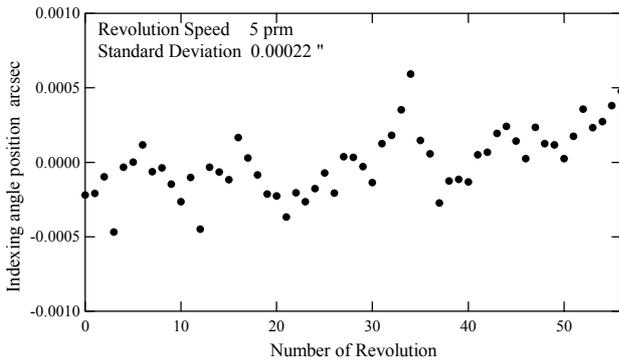


Fig. 4. Step indexing measurement

experiment, it finds out that the stability shows 0.00022".

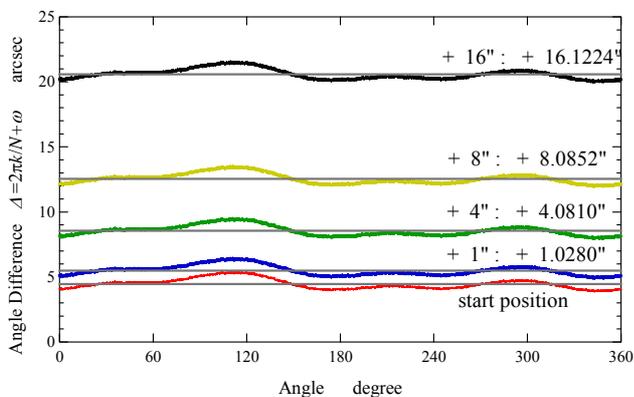


Fig. 5. Indexing stability

However, slightly angle drift is observed in the positive direction with time progress. One of reason of this angle drift is that the local form change inside this system by temperature change. It is the limit of the stability of this system.

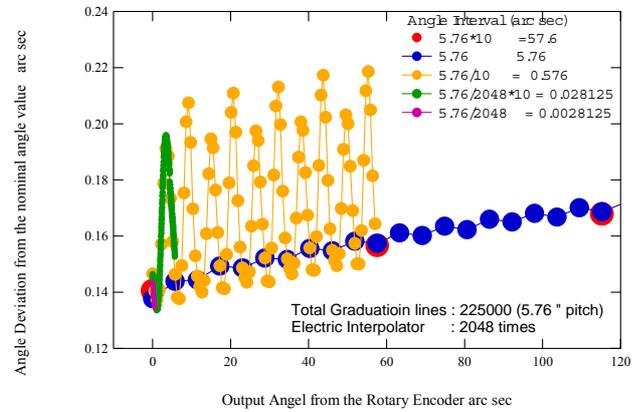


Fig. 6. Step indexing measurement

Fig.6 shows the indexing accuracy of read head A by the rotary encoder X. The ideal angle pitch interval of 225000 graduation lines is 5.76". The experiment which changed the moving step quantity of the read head A was carried out using 2048 division of electric interpolation. This result shows the indexing of 5.76" and 57.6" steps indicate the position of the graduation line, however the indexing step data of smaller than 5.76" indicate the one big amplitude sine curve caused by the electric interpolator error.

It turns out that this principle has a high precision also in the indexing position smaller than the scale pitch which a rotary encoder graduation has.

### 3. CONCLUSION

It was proved that the principle which applied the closed system of 360° of an angle makes the super-high precision indexing table on which indexing accuracy exceeds 0.001" by improvement in parts, such as air bearing. In this experiment, since it experimented using some equipment of National Metrology Institute of Japan, the angle drift under the influence of temperature etc. was detected. However, it is considered that more stable angle indexing system is realizable by developing the simplified system for this principle. It turned out that this principle is very useful for detecting the high accuracy angle and indexing from the wide range of 360° to the short range of 0.01".

### REFERENCES

- [1] Palmer, E.W., "High-accuracy angle measurement," NPL, Teddington, U.K. 1984.
- [2] Štěpánek, K., "Messung der Genauigkeit von Getrieben und Winkeln mit magnetischen Maßstäben," acta IMEKO, Proc. Int. Meas. Conf., 1st, pp. 258, 1958.
- [3] Xia, G.X., Wilkening, G.W., and Beyer, W., "Angle measuring instrument with integrating phase measurement," PTB Report PTB-F-4, 1988.