ROTARY ENCODER CALIBRATION

Michal Šindelář
Doctoral Degree Programme (1), FEEC BUT
E-mail: sindelar@feec.vutbr.cz

Supervised by: Petr Beneš
E-mail: benesp@feec.vutbr.cz

Abstract: Manufacturer of an encoder gives an information about maximum error level of the measured position and the magnitude of the angle deviation for each single position is unknown. The calibration provides an error map which can be used for correction of actual measured angle value. Hence, the measurement accuracy for each position is significantly increased. Presented method provides on-axis self-calibration and does not require any external angle standard. It is based on the interpolation of correct angle position for each count of the encoder.

Keywords: Angular deviation, angular position, calibration, encoders, position accuracy

1 INTRODUCTION

Rotary incremental encoders are widely used in many applications, such as aspherical machining, multi-axis manipulators, generally as drives feedback, or for astronomical telescopes positioning, etc. Not only these applications require high-accuracy angle measurement with sufficient resolution.

Manufacturer of the rotary incremental encoder guarantees absolute deviation in exactly determined running conditions, especially mounting tolerances, effects of the environment, and sufficient electronic processing (interpolator, frequency of a counter). The given value of the sensor's absolute error represents the worst case and affects all measuring points in the same way.

The result of the calibration process is represented by an error map, which provides the magnitude of angle deviations in certain measuring points. The error map obtained by the calibration allows correction of the angular values indicated by the sensor. Hence, the measurement accuracy for the given angle positions can be significantly increased. But there is a problem with different running conditions between calibration laboratory with precision rotary table and real industrial machine. T. Watanabe et al. in [1] states, that is impossible to achieve accuracy better than 0,01 arc-sec in angular measurement after installation of the encoder onto the application axis.

2 LIMITS OF ROTARY ENCODERS

The factors influencing the total accuracy can be divided into two groups. First group is represented by inherent errors and originates from the manufacturing process. Inherent errors mainly come from the scale disk of the encoder due to the non-uniform graduation, limited accuracy of scanning process, eccentricity of the optical pattern and geometric center of the scale disc, roundness of the scale or radial run-out of the integral bearing. The above mentioned and other similar influences are included in the specification of the sensor.

Operating and mounting influences represent the second group of the limiting factors. These acquired errors take significant part of the total error budget. The dominant deviation is caused by the encoder disk installation eccentricity. Reading head interprets the eccentrics movement as corresponding angle displacement. The resulting error has a sinusoidal course with frequency of the first harmonics. Radial run-out of the measured spindle has the same effect. Rotary encoders are available with or without integral bearing. If the encoder with integral bearing is considered, a coupling between the measured shaft and encoder shaft will introduce another error. Precision couplings decrease the angular accuracy by 0,5 up to 1,0 arc-sec [2].

In general, low order harmonics of the error map frequency spectrum correspond to the acquired errors, whereas high order harmonics represent the inherent errors. The above mentioned errors are in many cases repeatable (except radial run-out of a ball bearing) and can be corrected by the calibration values obtained during the calibration.

3 CALIBRATION METHODS

Calibration techniques can be divided into two categories. Firstly, methods referred to as cross-calibration arise from comparison of the tested sensor and the external angle standard. This calibration is performed in the calibration laboratory with precision rotary table in well-known conditions. Hence, this type of calibration approaches is laboratory sensitive and the obtained error map will be useless when the encoder is installed onto measured spindle.

Secondly, methods referred to as self-calibration represent the second group. In most cases these techniques employ suitable geometric layout of several reading heads in cooperation with the feature of a circle closure, which is applied as follows. The sum of the angles around any point in a plane equals 2π rad. As a result, this feature enables the independence of the self-calibration on the external angle standard. In addition, On-Axis variants of the self-calibration methods enable to perform the calibration of the encoder mounted onto its application axis.

One of the cross-calibration approach can be realized by employing two autocollimators and optical polygon. For example, this principle is applied in Czech metrology institute, more details in [3], or National Institute of Standards and Technology (U.S.). Angular accuracy of the polygon faces is not critical parameter. The degree of uncertainty of the method particularly depends on the alignment stability of a polygon mirror and axis of the autocollimator. Expanded uncertainty ($k = 2$) of the obtained error map reaches the level of 0,004 arc-sec [4]. On the other hand, National Metrology Institute of Japan has developed the angle encoder “Self-calibratable angle device” (SelfA), based on the EDA self-calibration approach [5], [6]. Angle comparator “WMT 220” from Physikalisch-Technische Bundesanstalt in Germany combines both principles and consists of two rotary tables. The inner table is coupled via autocollimator to the outer table, which contains the angle encoder with 16 reading heads and works in self-calibration mode, more information in [7].

3.1 EQUAL-DIVISION-AVERAGED METHOD

Equal-Division-Averaged Method (EDA) is one of the On-Axis self-calibration techniques, in which several sensor heads are installed at equal angular intervals around the scale disk. One of the placed sensors heads is reference. The output signals from the remaining sensor heads are compared with the signal from the reference head. Since all reading heads scan the same scale, the angle deviation contained in the output signal of the reference head is also contained in the output signals detected by the remaining heads with an appropriate phase shift. This phase shift is caused by the relative positions of the sensor heads. The differences between each output signal and reference signal are averaged for all graduations lines of the scale disc. The estimated average value represents the deviation from the nominal value [6]. For detailed description of the method see [8].

In National Metrology Institute of Japan, the EDA method has been implemented to the angle encoder SelfA. With 13 sensor heads is the SelfA applied to the japan national angle standard. The expanded uncertainty ($k = 2$) of the national standard is 0,01 arc-sec [9].

3.2 TIME MEASUREMENT DYNAMIC REVERSAL METHOD

Time Measurement Dynamic Reversal Method is the On-Axis self-calibration technique, in which only one reading head is required. The principle of the method is based on the precision spindle dynamics property in free response. The known dynamics of the spindle enables to estimate the value of the measured angular intervals of all measuring points of the encoder. Since measured pulse width of the incremental signal and corresponding angular interval of the scale are related through the spindle speed, the value of the measured interval in the angle domain can be obtained. Thus, the numeric model of the spindle dynamics is necessary. If there are discrepancies between the model and the real spindle dynamics, the accuracy of the method will be decreased. Therefore, the well-designed non-contact bearing for the spindle is required [10], [11]. In addition, the authors of the TDR use the numeric model with the second-order function.

The development of the TDR method is focused on the using more sensor heads evenly spaced around the optical disk, similar to the above mentioned EDA method. Since there is a known phase shift of the output signals, certain influences increasing the uncertainty (e.g. torsion vibration) can be eliminated. With four sensor heads the expanded uncertainty $(k = 2)$ is reduced to 0,006 arc-sec and first 500 harmonics are obtained [11].

3.3 DEVELOPED INTERPOLATION METHOD

Devised method is based on the free response of the spindle. However, the numeric model of the spindle dynamics is not applied. The reference time-dependence of the angle position is provided by interpolation. The input data for the interpolation of the reference curve are counts from the index channel of the tested encoder. The circle closure feature enables to obtain reference points with intervals exactly equal to 360°. Taking this information into account, a sequence of reference points will show trend, which the angle position is changed during the one revolution.

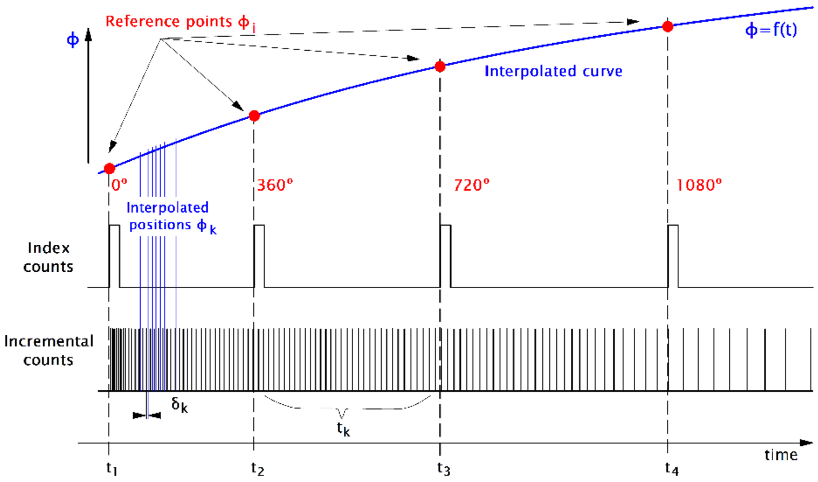

Figure 1: Principle of the developed method

The principle of the method illustrates Figure 1. The aim is to interpolate the actual value of the k-th graduation position ϕ_k for the measured time t_k of the k-th incremental edge. Thus interpolate function $\phi_k = f(t_k)$, where $k = 1, 2, \ldots, N$ marks the graduation line of the grating. The angle positions of the graduation lines indicated by the encoder are estimated by the measured time intervals between the incremental counts. Hence, the measured time intervals and angular positions are related through the interpolated function. Angular deviation is equal to the difference of the interpolated value and the nominal value. For the accurate results, the smooth function with the slow rate of change is assumed. From the measured free response of the spindle (Figure 2a) it can be seen, that the assumption of the smooth function is met.

For the interpolation a cubic Hermite spline was chosen, because of this method is well-suited for obtaining a smooth continuous function. Since we assume linearly decreasing rotating speed during each revolution, the interpolation by linear spline is inappropriate (angle position is equal to an integral of the angle speed, $\omega = d\phi/dt$).

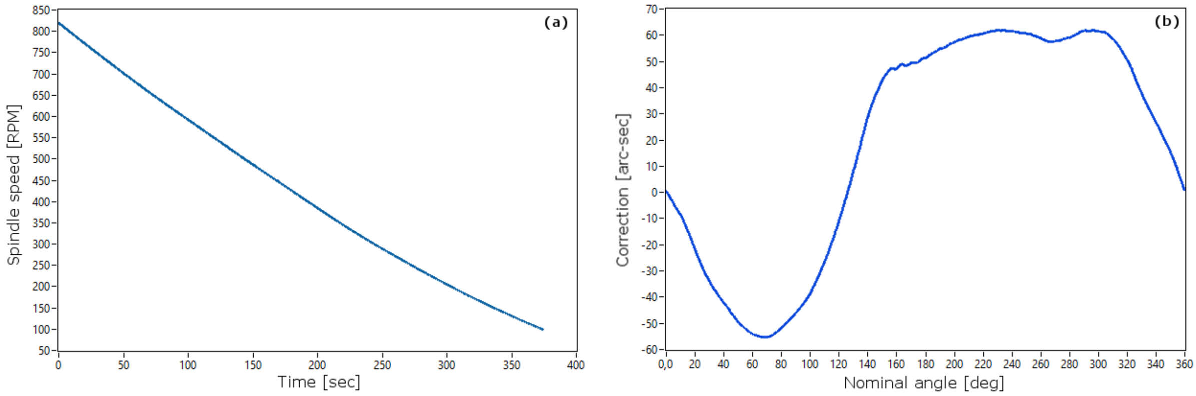

Figure 2: (a) Experimentally recorded spindle free response, (b) result of the calibration

The magnitude of the angle deviation $\delta_{i,k}$ is evaluated by the difference of the nominal and the interpolated value,

$$\delta_{i,k} = \Delta_k - \phi_{i,k}\,. \tag{1}$$

Index k marks the graduation line, index i represents given data set (i.e. revolution). The value of the nominal interval depends on the resolution of the encoder, $\Delta_k = k \cdot (360/N)$. The estimation of the error map is done for M consequent revolutions. Thus, the statistical factors influencing the measurement are eliminated. The averaged value of the angle deviation for the k-th graduation line can be expressed as

$$\bar{\delta}_k = \frac{1}{M} \cdot \sum_{i=1}^{M} \Delta_k - \phi_{i,k}\,. \tag{2}$$

For the method verification a calibration stage with appropriate measuring system was devised. The calibration stage employs a flywheel mounted onto a main spindle. The encoder under the test is coupled to this main spindle. The two ball bearings are installed for the spindle support. In order to eliminate motor driving torque disturbances during a free response the spindle motor can be turned off. The actual time of the count interval is captured by NI CompactRIO-9068 in cooperation with high-speed digital input module NI-9402. Since the fast acquisition rate is crucial, the time-critical part of the measuring application is implemented at the FPGA level. Implemented counter works with 200 MHz clock and enables to simultaneous capturing of three channels. The expanded uncertainty (coverage factor 2) of the measuring channel is 0,5 arc-sec at 780 RPM with 2048 counts per revolution. The tested rotary encoder specification is Allen-Bradley 844B-Z13C2048, system accuracy of ±150 arc-sec, and 2048 graduation lines [12]. Figure 2b shows the calibration result versus the spindle position.

4 CONCLUSIONS

This article has only been able to touch on the most general features of the precision angular measuring with rotary encoders and its calibration. On the above mentioned On-Axis self-calibration methods, the interpolation method and the calibration stage was devised. The verification of the presented method was accomplished by the calibration of the Allen-Bradley encoder. The obtained error map (Figure 2b) lies within the tolerance of the sensor. The level of the method uncertainty is presumed to 10 arc-sec. The exact evaluation of the uncertainty requires installation of the reference angle encoder. The method relies on the interpolation, in which the input data are counts from the index channel of the encoder under the test. The information is obtained solely once per revolution. So, this corresponds to the average speed in one revolution. As a result, the method is sensitive to the torsion vibration, because of lack of information how the actual speed is changing between each graduation line due to non-uniform friction of the ball bearings, flywheel imbalance etc.

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