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Development and Research of Miniature High Precision Modular Rotary Encoder Kit Based on Dual Optical Sensors

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***Abstract*—Open type modular rotary encoders are the most suitable choice for applications with limited installation space. The non-contact operating principle and bearing-free mechanical construction allow to design a compact, small size and lightweight angular position measurement device. However, the mounting and adjustment of the encoder have a significant effect on the accuracy that might be achieved. The runout of the measured shaft and the mounting eccentricity of the circular scale are important, because they cause and constitute the largest part of the error. In this work, the development of a miniature high-precision modular encoder kit is presented. It is based on the operation of combined dual optical sensors. The performed experimental research shows the effectiveness of the developed device and its ability to reduce mechanical installation errors by up to 99 percent.**

Keywords — Modular encoder, optical sensor, position error

I. Introduction

Rotary encoders remain the first choice for angular positioning and motion control in many industrial applications such as: high-performance servo systems, precise positioning applications, radar and tracking systems, robotics [1-6] as well as more sophisticated fields of medicine, military and surveillance or space technology. Rapid development of high technologies and constant increase in application areas require to push the development of the encoders in the direction of high-precision and miniaturization [7-10].

Open type modular encoder kit is particularly suitable for high accuracy applications with limited installation space. Its bearing-free design and non-contact optical working principle are perfect aspects that allow to develop a miniature hollow shaft encoder with no additional starting torque from shaft seal, compared to the closed type of rotary encoder. Its low weight and low mass moment of inertia make it well suited for dynamic applications with high accelerations and measured shaft speeds.

However, the attainable overall accuracy is mostly affected due to the mounting errors. Under the real working conditions, the circular scale of the encoder will have a certain eccentricity relative to the rotation axis (bearing) of the application shaft. The runout of the customer`s shaft as well as dimensional and form errors result in added eccentricity. The maximum angular position measurement error caused by eccentricity might be expressed as [11]:

$$\Delta\theta = \pm 412\frac{e}{D}, \quad \text{(I)}$$

where:

$\Delta\theta$ – measurement error in angular seconds,

e – eccentricity of the circular scale in μm (1/2 radial runout),

D – mean circular scale diameter in mm.

For example, 5 μm radial runout of the shaft with mounted 50 mm mean diameter circular scale will cause the maximum overall error of ±20.6 angular seconds, while a scale of twice the smaller mean diameter of 25 mm mounted on the same shaft will have the error of ±41.2 angular second. Thus, the smaller size encoders are more sensitive to installation errors making the miniaturization more challenging. Therefore, an extremely precise centering of the circular scale is needed in order to achieve high accuracy.

Despite the development of specially structured scale [12] or the use of sophisticated encoder cross-calibration and compensation algorithms [13,14], the integration of two optical sensors remains the most effective method [15,16] to reduce angular position measurement error caused by the eccentricity.

In this work Sec. II, the development of the miniature high-precision absolute optical encoder kit is presented. Its working principle is based on two combined optical sensors, that allows to eliminate the eccentricity error and ensure easy installation procedure and high accuracy. In Sec. III, the experimental research of ten prototype encoders is performed. The accuracy of the devices under the test is measured and the amount of error caused by a mounting inaccuracy is calculated by using harmonic analysis. In Sec. IV, results are summarized, and the performance of the developed encoder is discussed.

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II. Encoder Development

In this section, the development of the encoder is discussed in more detail. The designed modular encoder kit consists of two main parts: rotor and stator, as can be seen in Fig. 1. The main mechanical and electrical parameters are given below.

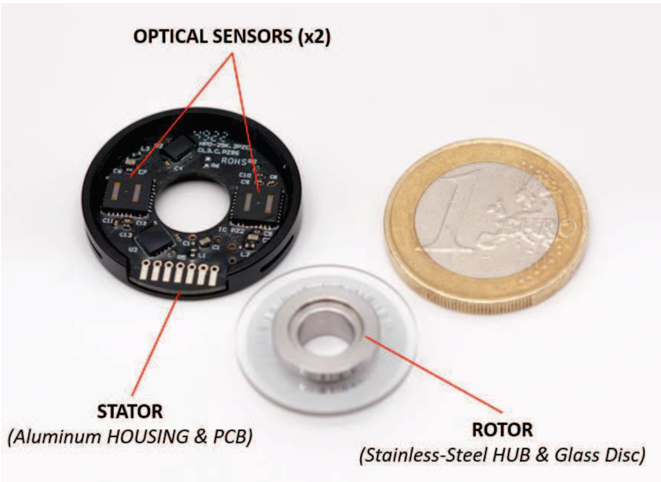

Fig. 1. View of developed modular optical encoder kit.

A. *Mechanical design of the encoder*

The main mechanical dimensions of the encoder are shown in the drawing Fig. 2.

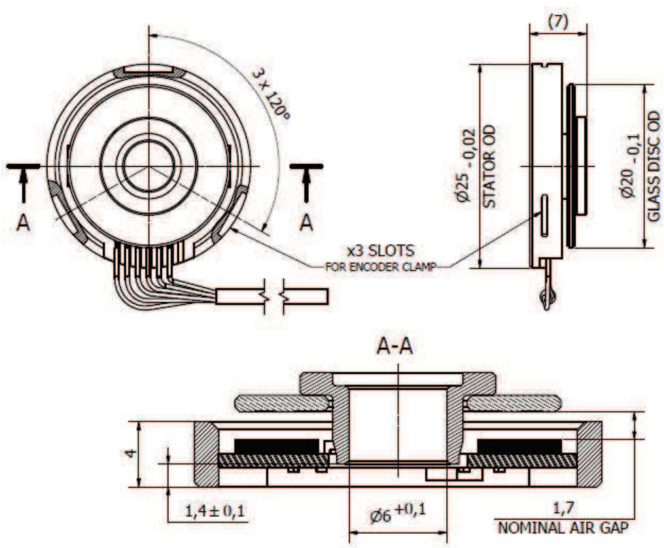

Fig. 2. Mechanical drawing with main dimensions of the encoder.

The stator is made of an aluminum housing with attached printed circuit board (PCB), that contains two high-resolution optical reflective absolute sensors [17] arranged at an angle of 180 degrees to each other. The outer diameter (Ø25 mm) of the stator housing is used for positioning, and the three slots on the side are used for stationary attachment to the application support by using special washers. The hole in the middle of the stator (PCB) is used for the customer`s shaft to go through.

The rotor of the encoder consists of a stainless-steel hollow-through hub and a glass disc with a circular scale pattern from chromium on it, formed by the photolithography process. The glass disc is optically centered according to the edge of the circular scale by using a microscope and is glued with UV-curable adhesive. The inner diameter (Ø6 mm) of the hub is used for the mounting on the shaft, which angular position must be measured. The hub is fixed with a bolt by screwing it into a threaded hole on the end of the shaft while pressing the encoder rotor in a stationary position. The mass of the assembled disc-hub unit is ~2 grams, and its mass moment of inertia is less than $6 \cdot 10^{-8}$ kg m^2.

The overall height of the encoder reaches up to 7 mm, and total mass (without a cable) is less than 10 grams.

B. *Electrical design of the encoder*

The absolute position measurement principle of the encoder is based on a reflective scanning of two circular pattern tracks: incremental and a maximum length sequence data code (M-code). The measured position data is transmitted by a bidirectional serial synchronous protocol BiSS-C [18]. This interface enables cyclic high-speed data transmission (up to 10 MHz) with line delay compensation, and safety capabilities, like CRC, Error or Warning data.

The principle electrical scheme of the encoder is presented in Fig. 3.

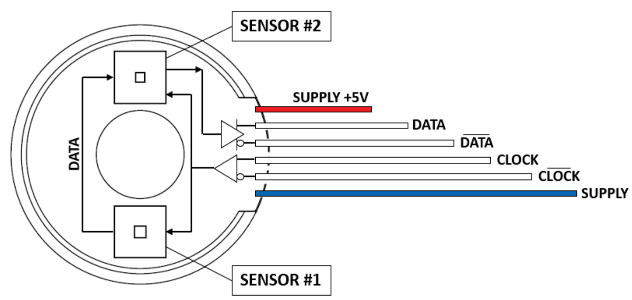

Fig. 3. The principle electrical scheme of the encoder.

A daisy-chaining of two optical sensors is implemented. The data from sensor #1 is sent to sensor #2. Whereas the latter transmits the combined position data of both sensors. The combined data then is sent over a single cable from the encoder to the BiSS-C master (e.g., drive / PLC). Despite the power supply lines of 5V, two lines of differential clock to the encoder, and two lines for differential data from the encoder are used to enable robust communication. The end user can use double word data and perform the averaged position calculation of two optical sensors in order to compensate for eccentricity and radial runout errors.

The overall system can assure resolution of 22 bits (4 194 304 positions per revolution) via built-in interpolation. Optical sensors, specially selected peripheral electronic components and the protective conformal coating ensure the proper operation under temperature conditions from –40 up to +125 degrees Celsius.

III. Experimental Research

Ten prototype encoders have been produced. Their calibration and accuracy measurement are performed by using JSC "Precizika Metrology" [19] technological equipment located in a thermo-stable laboratory. Each of the encoders is mounted on the technological comparator "BE187", which compares the angular position readings of the tested encoder with a reference high precision angular encoder. The difference between these readings is taken as an error of the encoder under the test. Such an accuracy measurement procedure is performed according to the international standard ISO 230-2. The unidirectional positioning error of the encoder is accepted as the system accuracy that defines the ± limits of the position deviations. The technological comparator "BE187" is tested and compensated by using autocollimator and can assure the measurement uncertainty of ±0.65 angular second.

The position data of each sensor is compared to a reference encoder and the system accuracy plot is generated. The calibration chart of one of the ten tested prototypes is shown in Fig. 4. It combines the position deviations of sensor #1 and sensor #2. The system accuracy of the presented encoder is ±712 angular seconds.

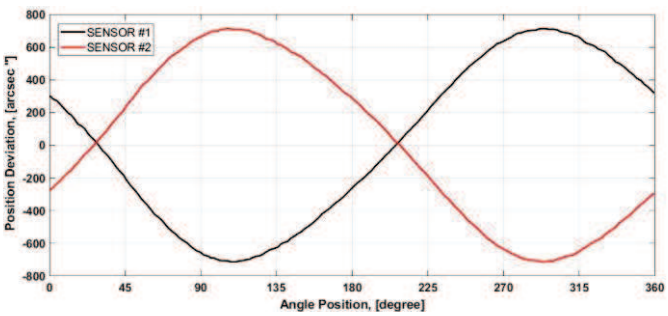

Fig. 4. Calibration chart of the developed encoder prototype: position deviation of sensor #1 (black line); position deviation of sensor #2 (red line).

Taking a closer look into the chart a major part of the error is caused by a first harmonic. I.e., the one period of sine shape is clearly seen in plots of both sensors. This is easily explained because the mechanical inaccuracies like eccentricity or radial runout occur like a first harmonic of the error plot profile. The actual size of this harmonic amplitude could be determined by applying the discrete Fourier transformation (DFT). The array of the recorded position deviation values from one sensor over 360 degrees is manipulated by using numeric computing environment „MATLAB" and the amplitudes of the Fourier components are calculated. The size of 1st harmonic amplitude of the sensor #1 shown in Fig. 4 is equal to 690.56 angular seconds. Knowing this size and using (1) it is possible to calculate the eccentricity:

$$e = \frac{AD}{\pm 412}, \quad (2)$$

where:

A – amplitude of the 1st harmonic in angular seconds,

e – eccentricity of the circular scale in µm,

D – mean circular scale diameter in mm (Ø16.38 mm).

The calculated eccentricity size of this encoder is 27.5 µm. It could appear due to the clearance of Ø6 mm diameter shaft fit to the encoder rotor or the radial runout of the shaft.

When the averaged position from both encoder sensors is used, the total system accuracy is greatly improved and reaches up to ±13.78 angular seconds. The deviation plot is presented in Fig. 5.

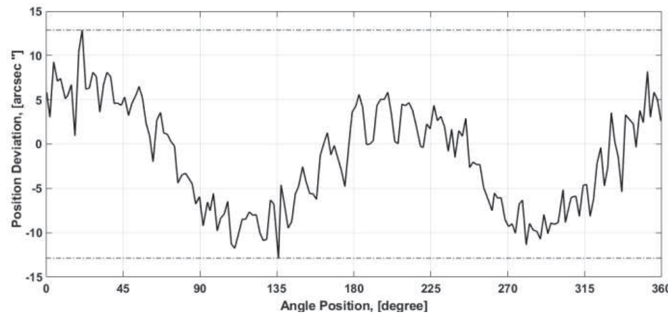

Fig. 5. Averaged position deviation plot of both optical sensors.

It is clearly seen that the first harmonic component is drastically reduced. The size of this component amplitude now is 2.12 angular seconds. Consequently, the error caused by eccentricity is reduced by 99.69 percent by using two sensors.

IV. Results

Same tests are performed to all ten encoders. Their accuracy by using one and both optical sensors are measured, and the values of 1st harmonic amplitudes are determined. The size of eccentricity is calculated by using (2). All collected data is provided in Table I.

The worst encoder accuracy of ±974.63 angular seconds is reached by using one sensor and with a predominant eccentricity of 38.3 µm. It was improved to ±25.37 angular seconds by using the averaged position reading from the two sensors.

The best accuracy (±52.8 angular seconds) of the encoder measuring angular position with one sensor is achieved when the circular scale had an eccentricity of only 0.7 µm. By using both sensors, the accuracy is improved up to ±8.96 angular seconds.

All performed measurements show that the accuracy of the optical modular encoder kit is significantly improved by using the combined dual sensors operation principle. The 1st harmonic of the angular deviation plot of the encoder using one sensor could be reduced up to 99 percent.

TABLE I. Experimental research data

Encoder No:	Positioning Error of 1 Sensor, [± arcsec "]	Positioning Error of Dual Sensors, [± arcsec "]	Eccentricity, [μm]	1st Harmonic of 1 Sensor Positioning Error, [arcsec "]	1st Harmonic of Dual Sensors Positioning Error, [arcsec "]	1st Harmonic Reduction [%]
1	712.85	13.78	27.5	690.56	2.12	99.69
2	310.30	17.38	12.3	308.36	7.40	97.60
3	682.75	11.09	26.4	663.87	0.78	99.88
4	552.37	13.08	21.8	549.35	3.50	99.36
5	742.25	21.10	28.2	710.43	4.81	99.32
6	841.17	25.29	33.2	835.31	3.88	99.54
7	974.63	25.37	38.3	964.36	4.91	99.49
8	52.87	8.96	0.7	17.61	2.64	85.01
9	359.07	17.83	13.4	336.21	3.33	99.01
10	133.22	12.87	4.2	104.26	1.60	98.47

V. Conclusions

The development of a miniature high-precision optical modular encoder kit is discussed, and the experimental research of ten produced prototype encoders is performed. After summarizing the results obtained during the research the following conclusions can be drawn:

1. The angular position measurement accuracy of open type modular encoder is greatly influenced by the mechanical inaccuracy of installation. Most of the measurement error is caused by the eccentricity of the circular encoder scale.

2. Determining the 1st harmonic, forming the overall system error, by applying the discrete Fourier transformation (DFT) and using the derived equation (2) is a convenient and simple method to find out the amount of eccentricity and what size of error it causes.

3. Implementation of two optical sensors placed at an angle of 180 degrees is an effective way to reduce the eccentricity error. The experimental study shows that the 1st harmonic of the measured error can be reduced by more than 99 percents.

4. The operation principle of dual combined optical sensors is easy to realize and does not require to apply a specific cross-calibration or compensation algorithms.

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