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# Development of a Specialized Microcircuit for a Magnetic Precision Position Sensor Based on Multipolar Magnetic Technology

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**Abstract**

The article presents the development of an specialized microcircuit of absolute position sensor with using a multipolar two-track magnetic system. The sensor design is based on the nonius principle of obtaining the absolute position code from the magnetic sensor system on the Hall effect with tracking angle-code converters. The results of the development and testing microcircuit and sensor systemare presented, which confirmed its operability.

**Keywords:** Position sensor, Encoder, Angle to code convertor

## INTRODUCTION

Position sensors based on the magnetic principle are widely used for rotary and linear position sensing. General direction for increase resolution and accuracy for this sensors is using multipolar magnetic systems. In this case, the magnetic system in conjunction with the sensor system and the processing circuit should ensure the determination of the absolute position. One way to create such a magnetic system is to use the vernier principle of stitching data from a system of two scales with a certain ratio of the periods of two or three magnetic scales [1, 2]. The key node of such a system is the sensor system and processing circuit. The sensor system can be implemented both on external magnetoresistors [3] and on Hall elements. Given the trends of miniaturization, increasing accuracy and reducing the cost of the system, it is most effective to integrate both sensor systems and the processing and stitching circuit into a single chip. Currently, the only commercially available microcircuit for Vernier magnetic position sensors is a single-chip solution containing Hall elements, conversion and stitching circuits - the iC-MU series of iC-Haus microcircuits differ in the size of the pole pairs of the magnetic system [4]. These microcircuits allow the use of magnetic disks with a fixed number of pole pairs of the main track in the amount of 16/32/64 and provide a position code with a resolution of up to 18 bits with a resolution of 12 bits per pole pair.

In this project, the task is to develop an absolute magnetic position sensor chip for the vernier scale. A feature of the development is the provision of signal processing from magnetic scales with any number of pole pairs, not necessarily a multiple of degree 2, as well as the adjustment of the sensor system for pole pairs of different sizes.

One of the main applications of the developed microcircuit is a rotor position sensor with a digital PWM output, which is built into the valve motor, for use in automotive electronics.

## CONCEPT OF VERNIER MAGNETIC POSITION SENSOR

Consider a system of 2 magnetic scales of the master track and the vernier track, consisting of 4 and 3 pairs of poles, respectively, Figure 1. The scales have a combined zero point, however, the number of pole pairs stacked for one measurement period differs by one.

The values of the position φm and φn of the master track and the vernier track, respectively, are determined independently from each other. Since the number of periods of the master and nonius tracks differ by 1, the position difference Φm-n = φm - φn for the period of measuring the absolute position is a linear function. From the phase difference Φm-n, the number of the current period of the master track N is uniquely determined. This, in turn, allows you to determine the current absolute position φA as:

$$\varphi A = \varphi m + N \cdot \varphi m\_max \qquad (1)$$

where φm_max is the maximum value of the period of the master track (the total number of discrete master tracks determined by the resolution of the conversion of the corresponding sensor system and the angle-code converter).

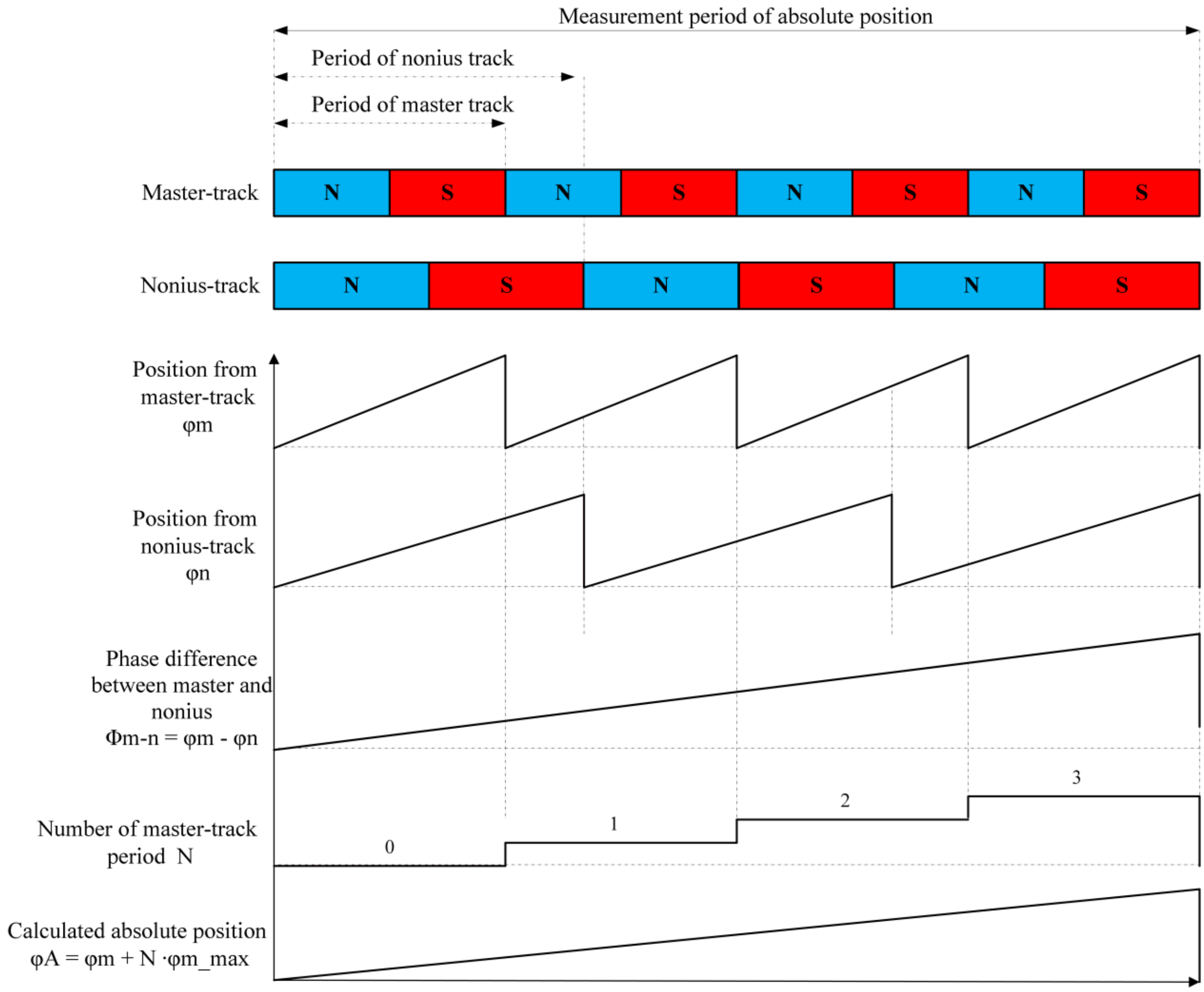


**Figure 1:** Principle of Vernier magnetic position sensor

If the conversion system for the master track has a resolution of 4096 samples per period, then the system considered in Figure 1 has a total conversion resolution of 4 × 4096 = 16384 samples, which corresponds to a resolution of 14 bits. Thus, the resolution of the conversion of the vernier system is defined as:

$$N_A = m \cdot N_M \qquad (2)$$

where

$N_A$ - is the number of samples on the whole scale;

m - is the number of periods of the master track;

$N_M$ - the number of samples for one period of the master track.

From formula (2) it follows that the maximum attainable conversion error, expressed in degrees, for the proposed algorithm is:

$$ErrT = 360 / (m \cdot N_M) \qquad (3)$$

The described concept allows you to create a position sensor with high resolution, the value of which is limited primarily by technological factors associated with the production of a coded magnetic disk with the required pole size. As a base for the developed sensor, the pole size of the master track of 2 mm was adopted.

## SPECIALIZED MICROCIRCUIT FOR VERNIER MAGNETIC POSITION SENSOR

Figure 2 shows the functional diagram of the developed microcircuit. The microcircuit contains sensor systems of master and vernier tracks, two servo-angle sensors, amplitude detectors master and vernier tracks, blocks for adjusting the current through Hall elements, a block for stitching and generating an absolute position code, a block for the sensor output interface, and an external I2C chip EEPROM to store tuning factors.

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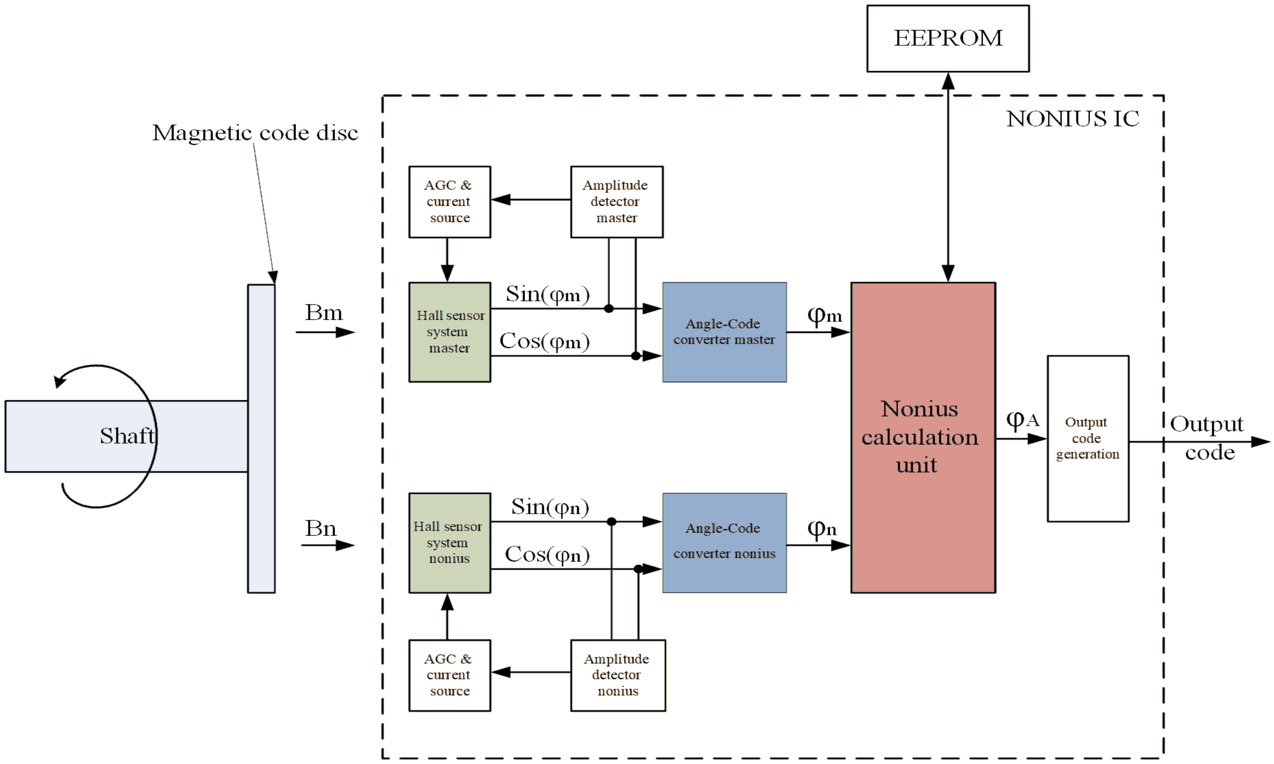


**Figure 2:** Functional diagram of specialized microcircuit for Vernier magnetic position sensor

The sensor systems of the microcircuit convert the magnetic fields of the magnetization tracks Bm and Bn into sine-cosine signals with phases corresponding to the position of the pole pair of the master and vernier tracks relative to the corresponding sensor systems. The sine-cosine signals of the sensor systems are converted into digital phase codes φm and φn of the master and vernier tracks by angle-code tracking converters.

The main issue in the development of a magnetic field transducer is the choice of the type of sensitive elements and sensor system. A sensor system based on Hall elements was selected. This choice is determined by two factors:

1) The ability to integrate Hall sensor elements into a standard technological route for manufacturing CMOS chips;
2) The level of magnetic field induction of the code magnetic disk is of the order of 15-50 mT at maximum, which is optimal for Hall elements.

A microcircuit sensor system was developed, consisting of 16 Hall elements located along the edge of the crystal. The converter microcircuit includes two such sensor systems - for master and nonius tracks, spaced on opposite sides of the crystal.

The signal from the Hall elements is amplified using current rotation technology [5] to eliminate the residual voltage and, by summing, is converted into a sine-cosine signal whose phase is proportional to the position of the pair of poles relative to the sensor system.

Each channel also contains an independent gain control system that maintains the amplitude of the signal at the input of the angle-code converter in a certain range regardless of the magnetic field induction. Such a system of automatic gain control ensures that the conversion error is constant regardless of changes in the distance between the code magnetic disk and the surface of the microcircuit, which are objectively possible during the operation of the sensor (the effect of vibration, mechanical assembly errors).

Angle-code converters are one of the key components of the chip as they determine the speed of the sensor as a whole. The requirement for the frequency of the output of the ADC is determined by the following expression:

$$f_{ADC} = R_{ADC} \cdot N_{PP} \cdot \frac{rpm}{60} \quad (4)$$

where $f_{ADC}$ is the transmitter output frequency, $R_{ADC}$ is the number of transducer readings per pole pair, $N_{PP}$ is the number of pole pairs of the disk, rpm is the required maximum speed of the sensor shaft expressed in rpm.

Based on (4) for a position sensor with a total resolution of 17 bits, the required rotor speed of 10 thousand rpm min and the resolution is 12 bits per pole pair, the angle-code converter must provide a data output frequency of at least 21.8 MHz (45.8 ns between samples). Such requirements severely limit the architecture of the angle-to-code converter. In practice, the following types of transducers are used in position sensor microcircuits:

- two linear ADCs + digital angle-based converter based on CORDIC in vector mode [6];
- two linear ADCs + digital tracking angle-code converter [7];

- arctangent ADC based on the architecture of sequential approximation [8];
- servo analog-to-digital angle-code converter [9].

High performance requirements of the vernier sensor significantly limit the choice of transmitter architectures. Thus, the use of either an ADC of sequential approximation, or even less a sigma-delta, becomes impossible. In essence, the choice remains between the ADC of the conveyor type with the CORDIC conveyor and the analog-to-digital servo-converter angle-code.

When designing the microcircuit, the architecture of the analog-to-digital angle-to-angle follow-up converter was selected, since in addition to high performance with moderate consumption, this architecture provides guaranteed monotonicity of the converter, which is very important for control systems.

The angle-code tracking converter (Fig. 3) includes two multiplying DACs, MDAC1, MDAC2, an error amplifier S1, an aperiodic Pi-reg link, a voltage controlled counting pulse generator (VCO), a reversible counter, and a digital sine-cosine signal generating unit Based on the counter code, the detector for entering the tracking mode (Lock detector). To create digital images, both ROM with written full sine and cosine codes, an abbreviated ROM with interpolation based on the least significant bits of the counter [9], and a formation unit based on the conveyor CORDIC [6] can be used.

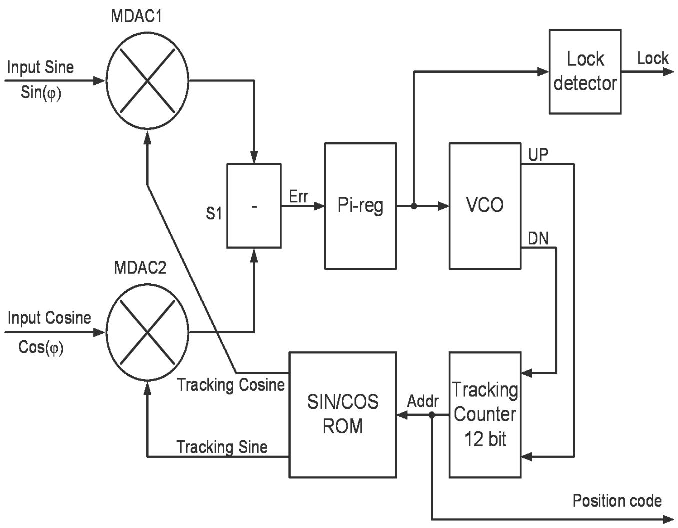


**Figure 3:** Structure of the angle-code tracking converter

The designed converter for maximum performance uses ROM with a full 13-bit sine and cosine code. The developed angle-code converter operates at a nominal clock frequency of 50 MHz while ensuring the maximum frequency of issuing samples in the tracking mode (tracking speed) of 25 MHz.

The microcircuit contains a unit for stitching data from two angle-code tracking transducers and generating an absolute position output code with a resolution of up to 17 bits. After stitching, the position code is sent to the conversion nonlinearity correction block, which eliminates the main trend of the conversion error.

The absolute position code φA obtained after "stitching" is converted by the interface unit into the desired form and is sent to the sensor output. The corrected position code is issued to the consumer via SSI, PWM, and incremental interfaces.

The microcircuit is developed using serial 180 nm CMOS technology. A photograph of the chip chip is shown in Figure 4. Die size is 4.7x4.4 mm.

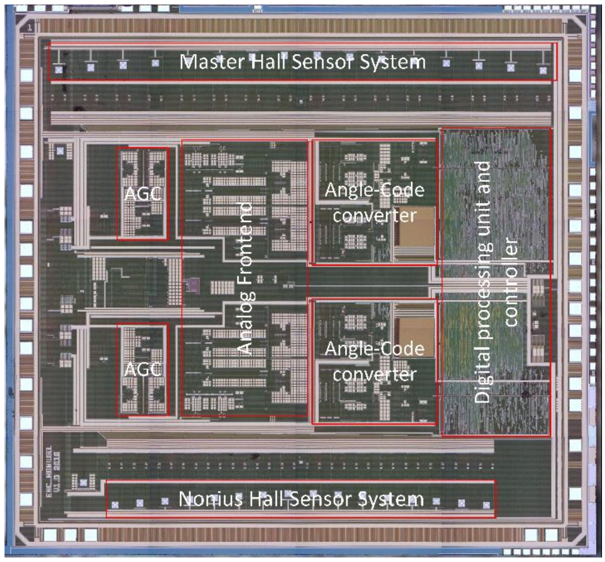


**Figure 4:** Photo of developed a specialized microcircuit for Vernier magnetic position sensor

**Research results of the developed microcircuit**

Microchip studies have been conducted. Table 1 shows comparative data on the results of the study of the angle-code converter of the developed microcircuit in comparison with other developments.

**Table 1**

| The angle-code converter | This work | iC-MU [4] | K1382HM025 [10] |
|---|---|---|---|
| Type of converter | Servo with sine-cosine ROM and multiplying DAC | Servo with sine-cosine DAC | Servo with CORDIC and multiplying DAC |
| Resolution, bit | 12 | 12 | 12 |
| Angle tracking rate, MHz | 35.0 | 26.2 | 4.0 |
| Current consumption, mA | 18 | ~15 | 10 |
| Area, $mm^2$ | 1.02 | unknown | 1.44 |

To study the microcircuit, a magnetic system was used, including two magnetic tracks with a pole pair size of 4 mm (for the master track) and the number of pole pairs 24 and 23 for the master and nonius tracks, respectively, Figure 5. The distance between the centers of the tracks is 3.6 mm . The amplitude value of the vertical component of the magnetic field induction at a distance of 1 mm is 82 and 73 mT for the master and nonius tracks, respectively.

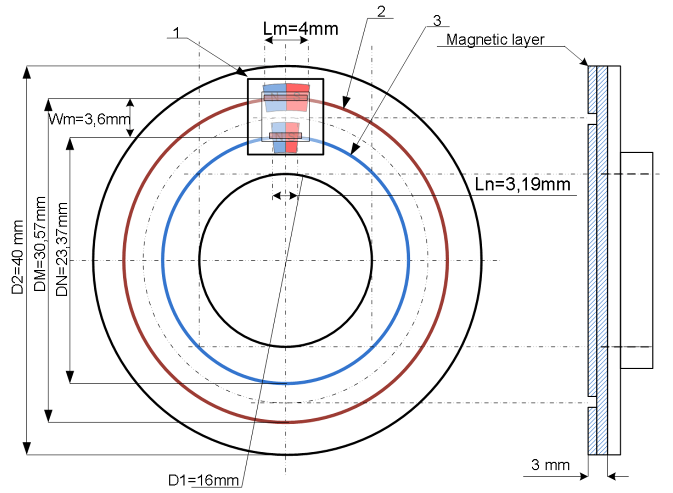


**Figure 5:** Magnetic system design, 1 - microcircuit, 2 - master track, 24 pole pairs, 3 - nonius track, 23 pole pairs

A circuit board with a microcircuit was installed on a specialized stand for the study of position sensors with a precision drive and a reference sensor. The distance between the disk surface and the microcircuit was about 1 mm. The structure of the stand is shown in Figure 6.

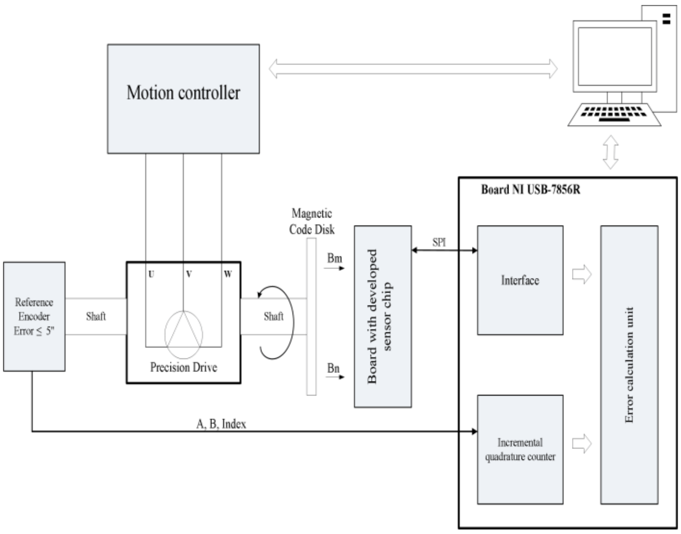


**Figure 6:** Research booth structure

Figure 7 shows a sensor board with an installed open-circuit developed microcircuit and a coded magnetic disk.

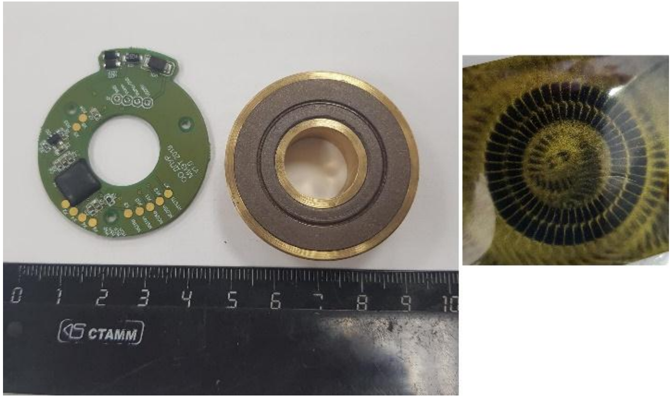

**Figure 7:** Sensor Board and Code Magnetic Disk 24/23 pole pairs (the magnetization pattern is shown in the figure on the right)

Studies of the developed microcircuit and position sensor were carried out, which showed the full operability of the presented concept. Figure 8 shows the results of the operation of the microcircuit: the outputs of the angle-master transducers and the vernier tracks, the phase difference between them and the absolute position code after stitching. The output code after stitching has an information capacity of 98304 samples, which corresponds to (2).

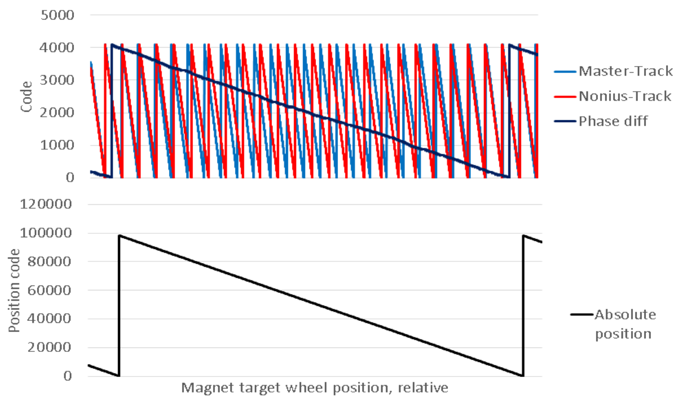


**Figure 8:** Vernier sensor conversion, measured data

The conversion error according to the measurement results was ± 0.2º. Figure 9 shows a graph of the sensor conversion error within a revolution.

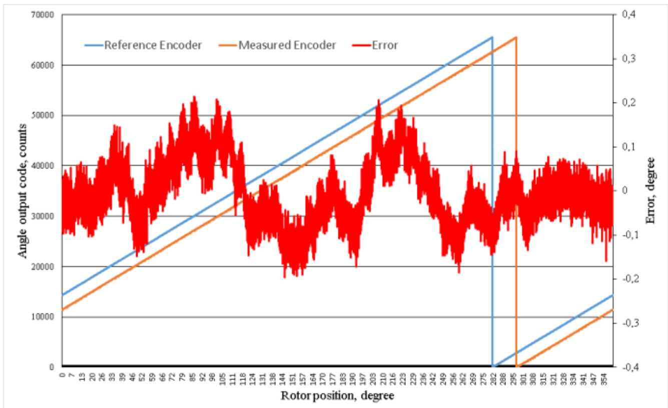


**Figure 9:** Error of developed sensor system

The measurements were carried out for several samples of code magnetic disks and showed the same result.

Table 2 shows the comparative results of the developed sensor with the Balluff BAV AS-LP-00008-01 sensor based on the iC-MU chip.

**Table 2**

| Parameters | This work | iC-MU (error present for sensor Balluff BAV AS-LP-00008-01) [11] |
|---|---|---|
| Maximum number of pole pairs | 32/31 | 64/63 |
| Pole size, mm | Adjustable base: 2.0/1.6 | Fixed: 1.28/0.96; 1.5/1.18; 2.0/1.66 |
| Possible number of pole pairs of the master track | Any even to 32 | Fixed 16/32/64 |
| Maximum Conversion Resolution, bit | 17 | 18 |
| Maximum rotation speed, rpm (for 17 bit) | 16 000 | 12 000 |
| Error of conversion, º | ±0.2 | ±0.2 |
| The distance between the magnetic system and the chip, mm | 1.0 | 0.4 |
| Maximum current consumption, mA | 87 | 81 |

## CONCLUSION

Studies of the microcircuit confirmed the operability of the developed system consisting of a position sensor microcircuit and a coded magnetic disk with two magnetization tracks. Using a code magnetic disk with the number of pairs of poles of the master track at 24, information capacity corresponding to the calculated one at 93804 counts per revolution and conversion error of ± 0.2 ° was achieved without the use of precision mechanical tuning of the sensor.

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