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ROTARY ANGLE SENSOR FOR MONITORING THE POSITION OF ACTUATORS

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Abstract. The reliability of actuators is determined by the criteria of limit states, which are assessed by different types of sensors. The reliability of sensors depends on their design properties, features of technological support of their quality in the manufacturing process. The angular position of the rotary links of actuators is determined by different types of sensors, including rotary angle sensors. A non-contact sensor is considered. The sensor operation is based on the Hall measurement principle, which ensures its structural simplicity, reliability and long service life. The accuracy characteristics of the sensor are determined by manufacturing errors of its individual parts. **The purpose of the study** is to develop a model of sensor error depending on manufacturing inaccuracies of the permanent magnet, which is part of its primary measuring transducer. **Materials and Methods.** The rotary angle sensor manufactured by Specialized Design Bureau "Induction" has been chosen as a prototype, during the production of which deviations in its technical characteristics caused by defects in the permanent magnets have been detected. The methods used in the paper include theoretical mechanics, calculation of electric and magnetic circuits, and numerical modelling. The calculations have been performed for a cylindrical permanent magnet with radial magnetization, wherein the magnetization vector is shifted in the radial direction. To perform the error calculations, the schemes of the arrangement of defective magnets relative to the magnetization vector of the external field created by additional magnets have been used. The coaxial arrangement of additional magnets is ensured by arranging them in coaxial cylindrical guides. **Results.** Analytical dependencies that relate the displacement of the magnet dipole relative to its geometric centre with the error in determining the rotary angle have been presented. The sensor errors have been shown in sketches of the primary measuring transducer in various positions of the magnet relative to the Hall elements in the primary transducer. **Conclusion.** The research results can be used in engineering facilities that allows for a quantitative assessment of the radial displacement of the magnetic dipole relative to the geometric centre of the magnet. The practical significance of the results lies in the rejection of permanent magnets at the stage of incoming inspection of the permissible displacement of the magnetic dipole relative to its geometric centre.

Keywords: sensor, sensitive element, Hall effect, magnetic dipole offset, error model

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ДАТЧИК УГЛА ПОВОРОТА ДЛЯ КОНТРОЛЯ ПОЛОЖЕНИЯ ИСПОЛНИТЕЛЬНЫХ УСТРОЙСТВ

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Аннотация. Надежность работы исполнительных устройств определяется критериями предельных состояний, которые оцениваются различными типами датчиков. Надёжность датчиков зависит от их конструктивных свойств, особенностей технологического обеспечения их качества в процессе производства. Угловое положение поворотных звеньев исполнительных механизмов определяется различными типами датчиков, в том числе датчиками угла поворота. Рассматривается датчик бесконтактного типа. Работа датчика основана на принципе измерения Холла, что обеспечивает его конструктивную простоту, надежность и длительный срок службы. Точностные характеристики датчика определяются погрешностями изготовления его отдельных частей. **Цель исследования:** разработать модель погрешности датчика в зависимости от неточностей изготовления постоянного магнита, входящего в состав его первичного измерительного преобразователя. **Материалы и методы.** В качестве прототипа выбран датчик угла поворота производства СКБ «Индукция», в процессе производства которого обнаружены отклонения его технических характеристик, вызванные дефектами постоянных магнитов. В работе использованы методы теоретической механики, расчета электрических и магнитных цепей, численного моделирования. Расчеты проведены для постоянного магнита цилиндрической формы с радиальной намагниченностью, при этом вектор намагниченности смещен в радиальном направлении. Для выполнения расчетов погрешностей использованы схемы расположения дефектных магнитов относительно вектора намагниченности внешнего поля, создаваемого дополнительными магнитами. Соосное расположение дополнительных магнитов обеспечивается путем расположения их в соосных цилиндрических направляющих. **Результаты.** Приводятся аналитические зависимости, связывающие смещение диполя магнита относительно его геометрического центра с погрешностью определения угла поворота. Погрешности датчика представлены на эскизах первичного измерительного преобразователя в различных положениях магнита относительно элементов Холла в первичном преобразователе. **Заключение.** Результаты исследования могут быть использованы в технологической оснастке, позволяющей дать количественную оценку величины радиального смещения магнитного диполя относительно геометрического центра магнита. Практическая значимость результатов состоит в отбраковке постоянных магнитов на этапе входного контроля допустимого смещения магнитного диполя относительно его геометрического центра.

Ключевые слова: датчик, чувствительный элемент, эффект Холла, смещение магнитного диполя, модель погрешностей

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Introduction

The rotary angle sensor [1] is designed to measure angular positions, coordinates of rotating drive elements, for example, on autonomous mobile equipment, in cranes, excavators, ships, offshore platforms, mobile and stationary waste compactors, controllers of controlled valves, as well as in robotics, on wind turbines, in large medical devices. In the listed objects, mathematical models of individual mechanisms can be represented in the form of manipulators with rotary joints, for which there is an analytical solution to the first problem of dynamics [2].

Analysis of the market and development trends of global sensor technology over the past 15 years clearly show that significant changes in directions and a reorientation of consumer interests in the area of application of precise position sensors are taking place in industrial automation and electric drives[1].

Until the beginning of the 21st century, optical rotary sensors (encoders), both incremental and absolute, both single-turn and multi-turn, occupied a dominant position in precision controlled drives. The mass demand for such encoders was facilitated by automation of production, digitalization of industry and control systems.

However, even mass production of optical encoders has not led to a reduction in prices for these devices. Approximate prices for absolute multi-turn encoders of the most popular sizes (with built-in digital interfaces such as Profibus, Ethernet, AS-i[2] and others) do not fall below the range of 1,000 to 2,000 Euros per encoder. For encoders for special and specialized applications (for explosion-hazardous areas, for industrial safety systems), the above prices should be multiplied by an increasing coefficient of 2 to 3.

There are two significant reasons for the high prices of optical encoders: complex and therefore expensive technology for manufacturing the code disk for the encoder, especially the multi-bit small-sized disk of the absolute encoder; complex and expensive technology for manufacturing the optical systems of absolute encoders. It is possible that the Kondratiev development cycle[3] for optical encoders is ending or has already ended [3]. New technologies are replacing encoders, in particular, the technology of precise magnetic measurements of the rotary angle, which is initially based on the technology of large integrated circuits.

This hypothesis is supported by the fact that magnetic encoders have come very close to the parameters of the best optical encoders in recent years, while the prices of magnetic encoders are many times lower. The magnetic encoder does not have the most expensive elements inherent in optics: a code disk and precise optical-mechanical elements, which significantly simplifies the design of the position sensor. Good accuracy and low price of a magnetic sensor may lead to the fact that in the foreseeable future the optical encoder will be forced out of the market.

Solutions for increasing the accuracy of angle sensors are known. In the 1979 author's certificate [4], a method and design of a shaft angle sensor for increasing the resolution capacity on technologies that are significantly inferior to modern capabilities are proposed. In the patent for invention [5], the accuracy is increased by complicating the design of the angular displacement sensor. In the utility patent [6], a modern arrangement of the elements of the angle sensor is used. However, the presence of an elastic connection of the support unit worsens the dynamic characteristics.

The articles [7, 8] consider mathematical models of sensors based on the Hall effect.

The article [9] provides a brief overview of miniature sensors of micro displacement, angular position and force based on the Hall effect.

The article [10] analyzes the state and development prospects of angular displacement measurement devices in 2014. The results of the analysis are relevant at the current time.

In addition, the problem of the domestic electronic component base has been well known since the times of the USSR − a shortage of cheap and accurate position sensors, without which it is impossible to create high-quality electric drives. It is possible that magnetic and some other areas of Russian sensorics will create the basis for a worthy replacement of the shortage of high-quality sensors.

The listed publications confirm the relevance of small-sized and sufficiently accurate magnetic sensors of the Specialized Design Bureau "Induction", their prospects and manufacturability.

1. Schematic Diagram of the Sensor

Fig. 1 shows the appearance of the angle sensor. The sensor includes a permanent magnet and a Hall element. The permanent magnet is installed on the axis of the sensor's rotary leash. The Hall element is built into a specialized microcircuit located on the sensor's printed circuit board inside the housing.

[1] https://www.sesese.org/Home/Publication?id=97.
[2] https://www.sesese.org/Home/Publication?id=97.
[3] Kondratiev waves represent a time cycle of 40 to 50 years, during which a rapid development of some innovation occurs.

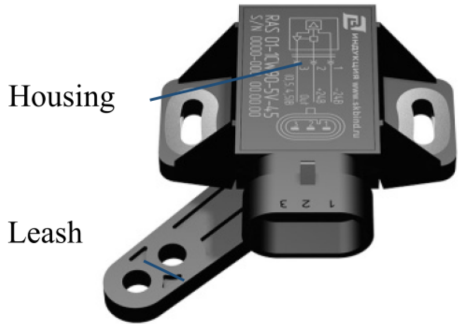

Fig. 1. External appearance of the angle sensor

The diagram of the angle sensor is shown in Fig. 2. The sensor contains a housing 1 equipped with a cylindrical projection 2. In the central part of the housing 1, in a bearing 3, an axis 4 of rotation of the sensor is installed, connected in its upper part with a movable (rotary) part 5. In the lower part of the axis 4, a permanent magnet 6 is fixed, made in the form of a diametrically magnetized disk, fixed coaxially with a sensitive element 7 in the lower part of the cylindrical projection 2 of the housing 1. The magnet 6 is located with a constant air gap equal to 0.5−1 mm, above a sensitive element 7 proportionate to it, installed with the possibility of constant contact on a printed circuit board 8 without the possibility of displacement in the housing 1 of the angle sensor. The printed circuit board 8 is connected by means of fastening elements 9 to the lower part of the cylindrical projection 2 of the housing 1, connected to the fixed part 10. The fixed part 10, having a proportionate opening for the cylindrical projection 2, is fixed to the upper part of the housing 1 by means of fastening elements 11, installed on the lower side of the housing 1. The movable part 5 is connected to the upper part of the axis 4 of rotation through a leash 12 fixed to the axis 4 by means of a fastening element 13. The movable and fixed parts 5 and 10 are located parallel to each other.

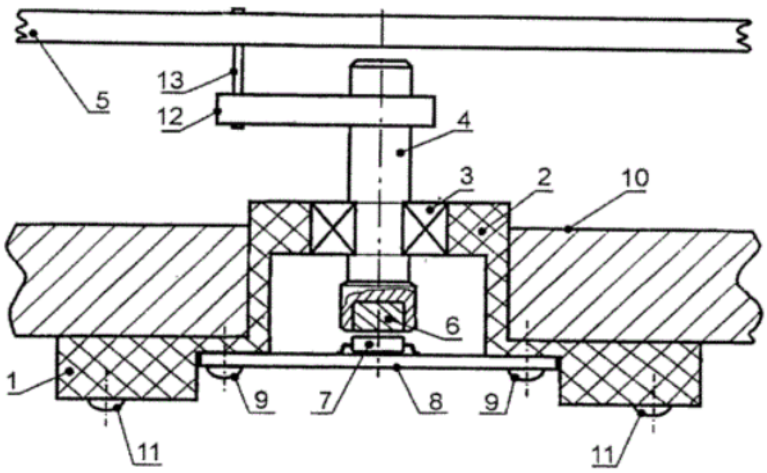

Fig. 2. Schematic diagram of the rotary angle sensor

The device operates as follows. Rotation of the permanent magnet 6 relative to the sensitive element 7 is provided by a rotor unit (not shown in the figure), mechanically connected from the outside of the rotary angle sensor to the movable part 5 with the help of a fastening element 13 by means of a leash 12, fixed on the axis 4. When the axis 4 with the permanent magnet 6 rotates, a change in the position of the magnetic field occurs, acting on the sensitive element 7, which registers the rotary angle of the magnet 6 and converts it together with other electronic components (not shown in the figure) of the printed circuit board 8 into an electrical signal of the required format, proportional to the magnitude of rotation and transmitted further to the registration device via a communication cable.

The complexity of the physical picture of magnetic fields arising during the manufacturing and operation of sensors with permanent magnets necessitates the development of mathematical models that take into account a large number of influencing factors [11, 12].

One of the main elements of the sensor, directly influencing the accuracy of the rotary angle measurement, is the permanent magnet 6. Fig. 3a shows a permanent magnet 1 of cylindrical shape with ideal diametrical magnetization: the magnetization vector 2 is located on the axis of symmetry of the magnet.

Fig. 3b shows a permanent magnet 1 of cylindrical shape with non-ideal diametrical magnetization: the magnetization vector 2 is radially shifted relative to the axis of symmetry of the magnet by the value Δ*M*.

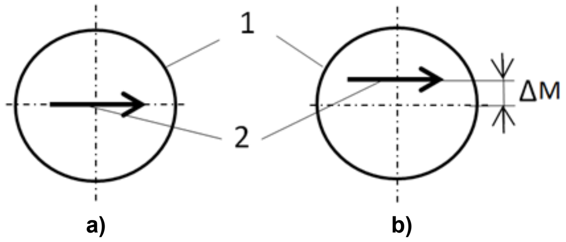

Fig. 3. Magnetization diagrams

Fig. 4a shows the magnet arrangement diagram corresponding to its zero initial position $\alpha = 0°$. In this position, the measured angle value $\alpha^* = -\alpha_0$. The sign "–" is used to count the angle counterclockwise. The measured angle value, caused by the radial shift of the magnetization vector, is the sensor zero signal shift. To correct the measured value, it must be added to the zero shift: $\alpha = \alpha^* + \alpha_0$. Fig. 4b shows the magnet position for a rotary angle in the range from 0 to +90°. Fig. 4c shows the magnet position for a rotary angle of +90°.

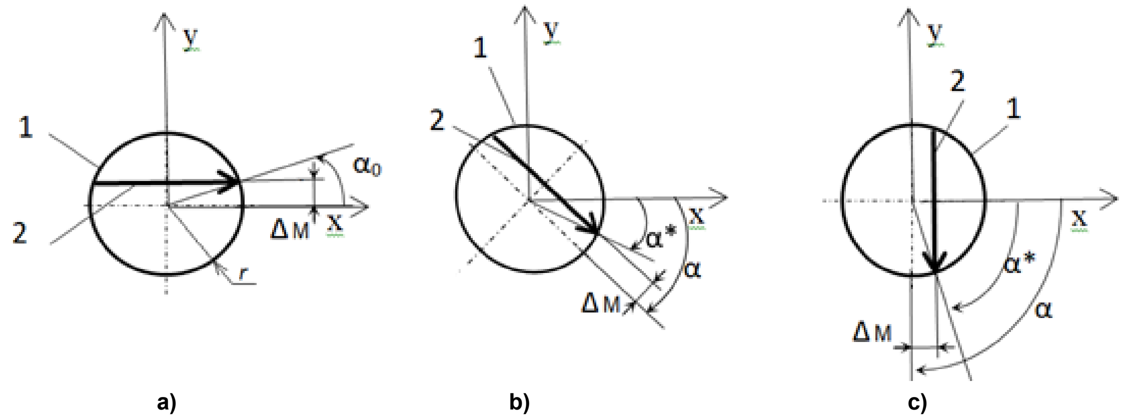

Fig. 4. Schemes for calculating the error

2. Mathematical Model of Errors

For an arbitrary rotary angle of a magnet with a radius r, the relationship between the sensor zero error and the displacement of the magnetization vector has the form:

$$\alpha_0 = r \arcsin(\Delta M / r). \tag{1}$$

The sensitivity of the sensor zero error to the error in the nominal radius of the magnet is obtained by applying the partial derivative with respect to the variable r to expression (1):

$$\frac{\partial \alpha_0}{\partial r} = -\frac{\Delta M}{r^2 \cdot \sqrt{1 - \frac{\Delta M^2}{r^2}}}. \tag{2}$$

The sensitivity of the sensor zero error to a change in the position of the magnetization vector is obtained by applying the partial derivative with respect to the variable Δ*M* to expression (1):

$$\frac{\partial \alpha_0}{\partial \Delta} = \frac{1}{r \cdot \sqrt{1 - \frac{\Delta M^2}{r^2}}}. \tag{3}$$

Using expression (2), we obtain an expression for the absolute dependence of the sensor zero error on the magnet radius error:

$$\Delta\alpha_0(\Delta r) = -\frac{\Delta M}{r^2 \cdot \sqrt{1 - \frac{\Delta M^2}{r^2}}} \cdot \Delta r. \tag{4}$$

Using expression (3), we obtain an expression for the absolute dependence of the sensor zero error on the change in the position of the magnetization vector:

$$\Delta\alpha_0(\Delta M) = \frac{1}{r \cdot \sqrt{1 - \frac{\Delta M^2}{r^2}}} \cdot \Delta M. \tag{5}$$

Fig. 5 shows the graphs of the sensor zero error from the magnetization vector shift according to expression (1). The graph can be used to numerically estimate the sensor zero error.

Fig. 6 shows the graphs of the sensor zero error according to expression (4) from the change in the magnet radius. The given graph is relevant for the case of algorithmic compensation of the error according to expression (1). During the operation of the sensor, under the influence of external disturbances of various natures, a change in the radial displacement of the magnetization vector is possible, which will lead to the appearance of an error.

Fig. 7 shows the graphs of the sensor zero error depending on the magnet radius and the displacement ΔM of the magnetization vector according to expression (5). The given graph of the error is relevant for the case of a change in the ambient temperature. Expression (5) can be used for algorithmic compensation of errors caused by a change in the magnet radius. The same expression will allow justifying the choice of the tolerance field for the nominal size of the magnet diameter at the stage of its design.

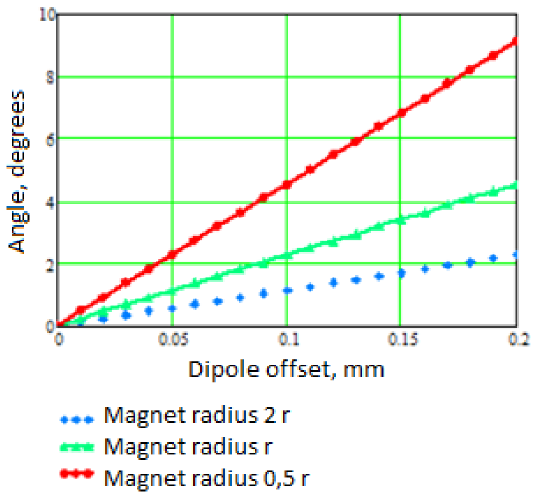

Fig. 5. Sensor error from magnetic dipole offset

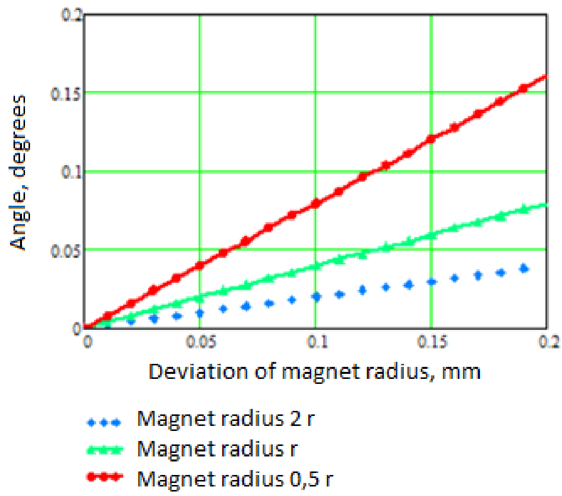

Fig. 6. Sensor error caused by changes in the radial displacement of the magnetization vector

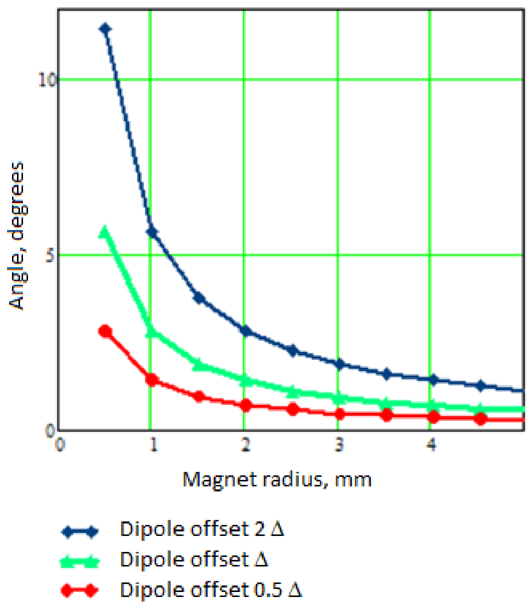

Fig. 7. Sensor error frcaused by changes in magnet radius Δ

In [13], the use of an acoustic sensor for assessing the state of production equipment, which can be used to automate the installation of incoming inspection of permanent magnets, is proposed. A prototype of the installation for automatic inspection of permanent magnets is presented in [12, p. 470].

3. Schematic Diagram for the Magnetic Dipole Position Monitoring Device

Fig. 8 shows a diagram of a technological device for monitoring the position of the magnetization vector of a permanent magnet. Two permanent magnets with magnetization vectors $M1$ and $M2$ are installed coaxially in the device. A channel is made in the transverse direction relative to the longitudinal axis of the device, which serves as a guide for the magnet M being tested. If the magnetization vector M of the magnet being tested is not shifted relative to its geometric center, then the diametrical axis is on the same axis as the magnetization vectors $M1$ and $M2$, as shown in Fig. 8.

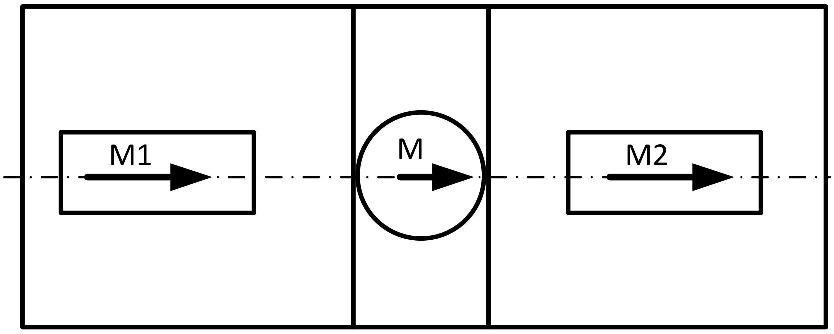

Fig. 8 Position of an ideal magnet in the technological device

Fig. 9 shows the shifted position of the defective magnet relative to the longitudinal axis of the technological device by the value ΔM – the shift of the magnetization vector of the permanent magnet M.

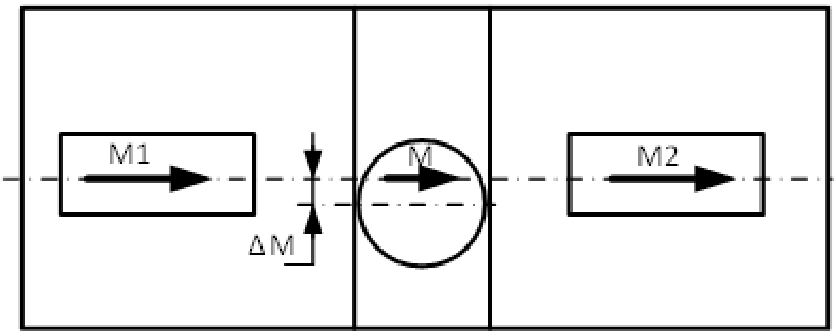

Fig. 9. Position of the defective magnet in the technological device

In [14], a numerical method for processing the results of dynamic measurements, which will reduce the time for assessing the state variables of the controlled object, is considered.

In the conditions of real operation of the angle sensor, its mathematical model in a stochastic formulation is relevant. In this case, it is possible to use the algorithm of adaptive guaranteed estimation of a constant signal under conditions of uncertainty of measurement errors [15].

Conclusions

The conducted research allowed forming a mathematical model of the error of a non-contact rota angle sensor, built on the Hall effect, containing a permanent magnet in its composition. Based on the mathematical model of the error, a schematic diagram of the technological device has been developed, which allows excluding defective magnets from production at the stage of incoming inspection.

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