Choosing the method for determining angular motions of motor vehicle electromechanical subassemblies

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Abstract

The most common methods and devices for determining the rotational angle of electromechanical subassemblies (RAEMSA) of motor vehicles were analyzed. The analysis showed that the incremental method proves to be the most favorable for automobiles involving a synchronization disk and a digital Hall sensor for mechanisms that make a full rotational movement, AMR sensors for mechanisms operating in a limited sector of the rotational angle. An algorithm for processing the sensor signals to expand the measuring range for the angle of the operating mechanism position has been developed. This algorithm allows doubling the measuring range for the angle of the working mechanism position.

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1. Introduction

Based on the current trends of social development, it can be declared that year by year automobile transport (AT) has been increasingly used throughout the world. The main criteria for an automobile are: safety, reliability, efficiency, environmental friendliness, comfort. They are achieved in many ways. For example, by using electric vehicles, developing the ways to reduce noise and vibration [1–4], using alternative energy sources for transport [5–7], working out effective maintenance and repair methods [8], designing traffic stabilization systems [9], etc.

According to the data in [10], the sales of plug-in electric vehicles had reached 2 million by 2020. This is due to the fact that technological solutions are being developed all over the world to facilitate the spread of electric vehicles in large cities and metropolises [11–13].

As it is commonly known, a modern car has a large number of electromechanical components and systems. The tasks of these systems are determining the control actions and the current state of rotating units, positioning mechanisms, etc.

Such systems include:

- an electronic engine management system (EMS). Its task is to ensure the correct operation of one or more engine systems. It controls the fuel system, the cooling system, the fuel mixture intake and exhaust system, the brakes system, the gasoline vapor recovery system, etc. [14];
- systems for adjusting headlights, mirrors, driver and passenger seats [15-17];
- suspension height adjustment system [18, 19];
- anti-lock braking system [20, 21].

The main element of most of these systems is the electric motor (EM). During the operation of these systems, the problem of determining the position of the moving mechanism is constantly being solved, both in relative and in absolute values. The automotive industry places high demands on EM control. Accurate information about rotor speed and position is essential for precise control over the torque and speed. This ensures

maximum efficiency of the EM, and also enables to increase the range of motion and improve comfort and safety of vehicles. In addition, real-time information about the speed and position of the rotor is required for a certain direction of a start from an idle position and prevention of unintentional blockage of the transmission [22].

According to the principle of operation, rotary mechanisms can be divided into those which make:

- rotational movements in one direction;
- rotational movements with reverse;
- incomplete rotation in a given angular range.

In connection with such a variety of rotary mechanisms, the problem of determining the angular position of mechanical subassemblies has different solutions.

Therefore, the purpose of this work is to select the method and devices for determining the angular motions of motor vehicle electromechanical subassemblies, which allow expanding the measuring range for the angle of the working mechanism position.

To achieve this goal, it is necessary:

- to study the most common methods and devices for determining the rotational angle of electromechanical subassemblies (RAEMSA) of motor vehicles;
- to choose the most optimal method for determining the RAEMSA;
- to develop an algorithm for processing the sensor signals to expand the measuring range for the angle of the working mechanism position.

2. Actual methods and devices for determining RAEMSA

RAEMSA in automobiles can be identified in various ways. These ways are based on contact and non-contact technologies [22].

As it is known, according to the principle of operation, they are divided into optical, resistive, magnetic, inductive, mechanical; according to the permissible angle of shaft rotation, they are divided into sensors with a limited operating range and sensors with an unlimited operating range.

In the simplest case, a special synchronization disk with one or two inductive-type sensors or Hall sensors is used to measure the speed and angular position of a mechanism rotating in one direction (Fig. 1) [23, 24].

This method is relatively simple and inexpensive, but its accuracy depends on the number of marks on the synchronization disk and on the rotation speed. In addition, in order to begin determining the angular position, the disk must make a complete revolution to the mark corresponding to the initial position [25].

In the automobile, this method is used in EMS to determine the angle of the crankshaft rotation and in anti-lock braking systems to determine the speed of the wheels

rotation. This sensor is not applicable for mechanisms that make an incomplete turn in a given sector. In this case, resistive sensors are used [25], which represent a linear variable rotary resistor (Fig. 2) [26].
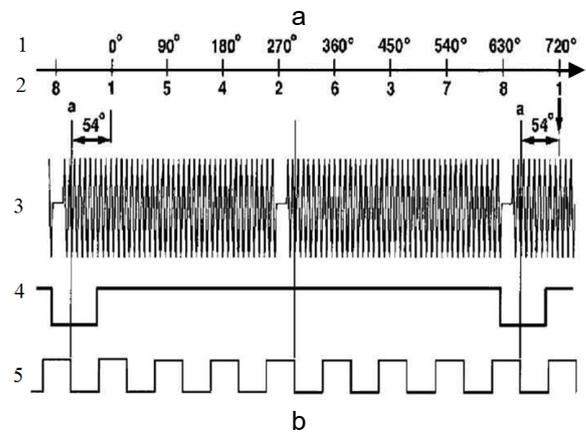

Figure 1. Synchronization disk with the angular position sensor: (a) exterior view [23]; (b) oscillogram: 1 - crankshaft rotational angle; 2 - cylinder number; 3 - signal from the crankshaft position sensor; 4 - signal from the Hall sensor of the camshaft position; 5 - engine speed signal
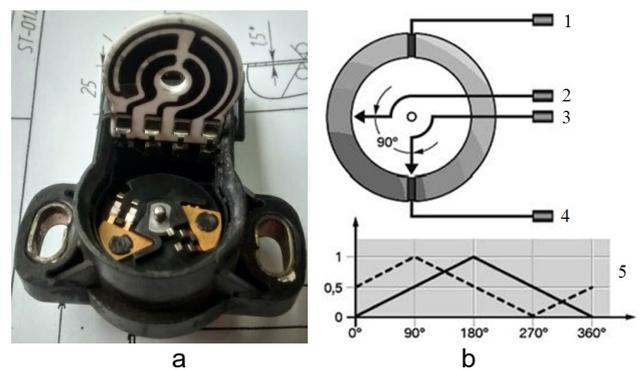

Figure 2. Resistive angular position sensor: (a) exterior view; (b) principle of operation: 1 - reference voltage; 2 - voltage on sliding contact 1; 3 - voltage on sliding contact 2; 4 - ground contact; 5 - the rotational angle of the rotating mechanism

The sensor shaft is attached to the axis of rotation, and the stator – to the stationary part of the housing. When the shaft is turning, the resistor changes its resistance. The

resistance value corresponds to a certain angle of the mechanism rotation.

The drawback of resistive sensors is their short life. Mechanical friction of the moving contact against the resistive material causes its wear. Another reason for the failure of the resistive sensor is dirt contamination, which leads to the loss of function of its working surface.

In automation systems, encoders are used as rotation angle sensors.

An encoder is a device, whose shaft is connected to the rotating shaft of the investigated object, and provides electronic control of rotation angle of the latter [27].

By the principle of operation, encoders are divided into optical and magnetic [28, 29].

On the shaft of the optical encoder, there is a disk with interruption windows along the perimeter, opposite which there is a LED and a phototransistor, which provide the formation of the output signal in the form of a sequence of rectangular pulses with a frequency proportional to the number of interruption windows and the rotation speed of the disk/shaft. The number of pulses indicates the angle of rotation. Encoders are divided into incremental and absolute.

Absolute encoders (AE) can be extremely accurate. They can be operated via bus interfaces [27], Fig. 3.
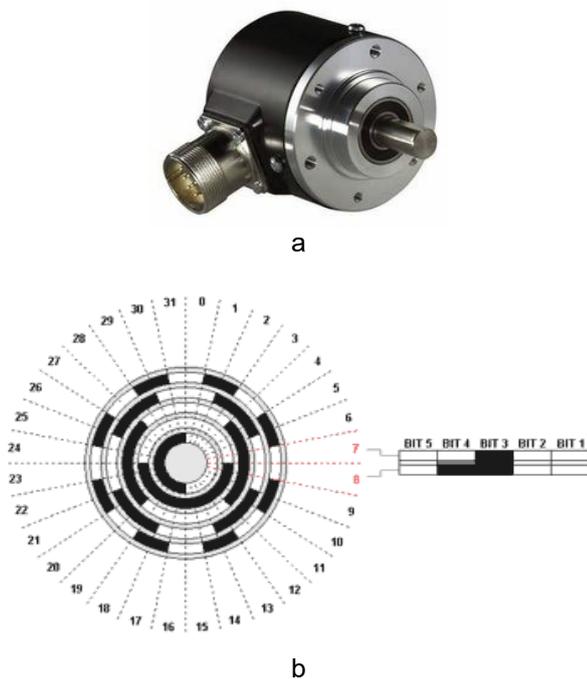

a

b

Figure 3. Absolute encoder: (a) exterior view; (b) principle of operation

The AE has an interrupt disk with concentric windows at different radii, whose relative sizes are determined by the binary code, and which are read out simultaneously, giving a coded output signal for each angular position (Gray code, binary code). In this case, it is possible to obtain data about the instantaneous position of the shaft

without a digital counter or return to the original position, since the output has a coded word – "n bit", protected from electrical noise.

The main operating characteristic of AEs, both optical and magnetic, is the certain number of steps, that is, the number of unique codes per revolution and the number of such revolutions [4].

AEs are used in applications that require the mandatory storage of incoming data for a long time. However, they are more complex in design and more expensive than incremental encoders. AEs meet requirements such as accuracy, reliability, increased wear resistance for a long period of operation.

Incremental encoders (IE) are designed to determine the rotation speed and rotational angle of rotating objects. They generate a sequential pulse digital code containing information about the rotational angle of the object (Fig. 4) [26].
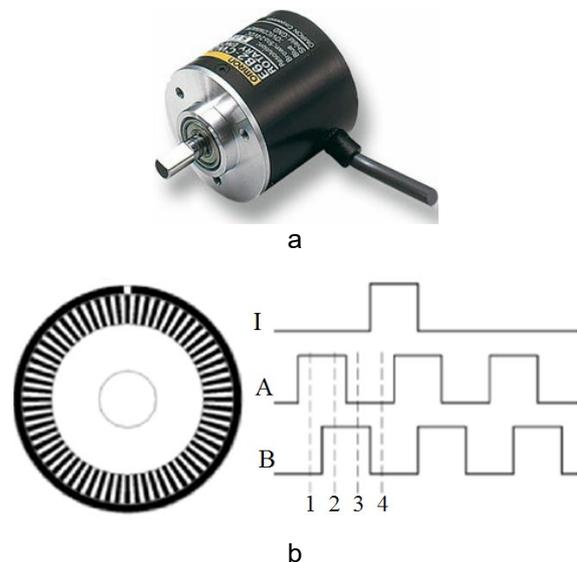

a

b

Figure 4. Incremental encoder: (a) exterior view; (b) principle of operation

IEs have an interruption disk with many windows of the same size on the main radius and two readout optocouplers (outputs A, B), Fig. 4. This allows fixing the rotational angle and the direction of rotation of the shaft. On the auxiliary radius of the disc, there is one interruption window and a corresponding optocoupler (output I), which determine the initial position (reference point).

The main operating parameter of the IE is the number of pulses per revolution. The instantaneous value of the angle of the object's rotation is determined by counting the pulses from the start. To calculate the angular velocity of the object, the processor in the tachometer differentiates the number of pulses in time, thus immediately showing the speed value, that is, the number of revolutions per minute. The output signal has two channels in which identical pulse trains are offset by 90°

relative to each other, which makes it possible to determine the direction of rotation. There is also a digital zero-mark output.

The drawback of IEs is that they give a relative readout of the rotational angle, information about which is not saved when rotation is stopped. Their advantages include simplicity of design, as well as the low cost at high resolution and high operating frequency.

The most common types of signal outputs are the parallel code, Profibus-DP, CANopen, DeviceNet, SSI, LWL interfaces, through which the sensors are also programmed. The presented sensors have high resolution up to 36 bits and do not require initial installation and initialization of the sensor.

Encoders are not widely used in automobile control systems. This is due to the fact that they are relatively large in size, more complex in design and more expensive.

Anisotropic magnetoresistive (AMR) sensors are gaining popularity today for the purpose of determining the angle of rotation of a mechanism operating in a limited sector where the sensor size matters.

AMR sensors are characterized by high sensitivity, high levels of primary signal, wide operating temperature range, robustness, reliability and accuracy. In addition, they are characterized by small offset and significant insensitivity to magnetic and mechanical influences (tolerances). They are used to create a wide variety of sensors for various applications, in particular for automobile electronics, industry and navigation systems.

The principle of operation of AMR sensors is based on the use of an anisotropic magnetic effect, that is, on the ability of a magnetoresistive material, for example, a permalloy (NiFe) film, to change resistance depending on the mutual orientation of the flowing current and the magnetization vector of the magnetic domains of the film [5]. An external magnetic field returns the film magnetization on angle α. In this case, the resistance of the film changes: the minimum resistance of the film corresponds to angle α = 90°, and the maximum value of the resistance corresponds to angle α = 0.

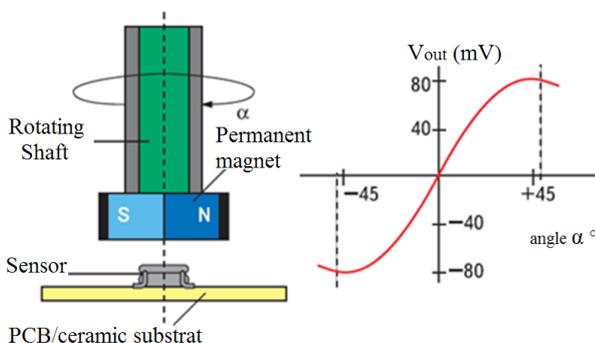The principle of measuring the angular position is shown in Fig. 5 [30].

Figure 5. Measuring the angular position with the AMR sensor

A dipole magnet is attached to the shaft end. When the magnetic vector rotates by angle α, the resistance and output voltage of the sensor change, and by this change the shaft rotation angle and direction (within ± 45°) can be determined.

In order to measure the angle of rotation within ± 90°, two sensors are combined, offset from each other by 45°. This principle is explained in Fig. 6 [30].
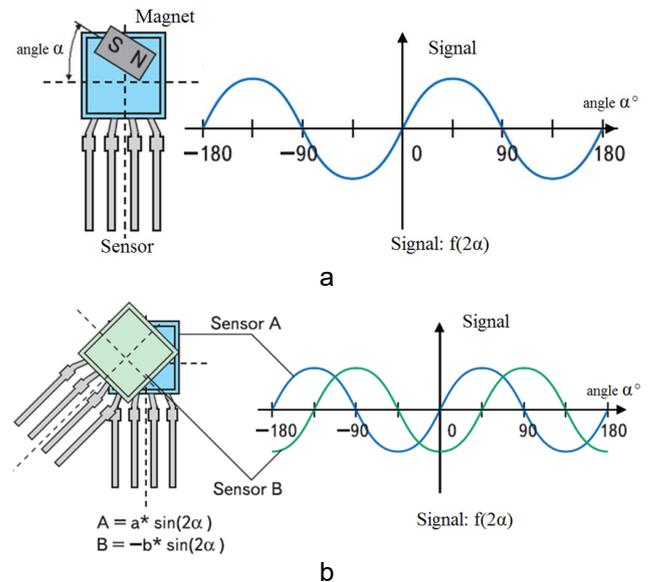

Figure 6. Angle measurement: (a) ± 45°; (b) ± 90°

AMR sensors are used in automobile electronic systems to measure the rotational angles of the throttle valve, gas pedal, seat position, headlight range control, body lift height, electric drive rotor position.

3. Determining the rotational angle of the mechanism using the AMR sensor

To study the methods for measuring the angular motions of motor vehicle electromechanical subassemblies, an integrated microcircuit of NXP company - KMZ60 was used as an AMR sensor.

KMZ60 combines two integrated circuits in one housing: a rotational angle sensor and an instrumentation amplifier, Fig. 7 [31].

The two transducer bridges of the sensor are offset at 45° to each other. In this arrangement, the two outputs show an electrical phase offset of 90°. Thus, the two signals are proportional to sin2α and cos2α, respectively. It can be easily proven that these two signals provide an angular range of 0 to 180°.
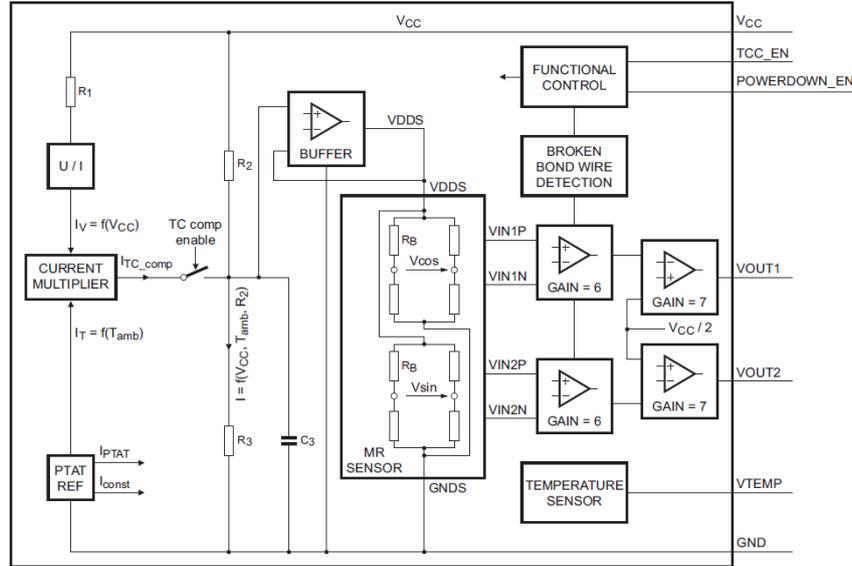
Figure 7. Functional diagram of KMZ60 sensor

Let's assume that neither output has offsets, or that earlier the offsets have been compensated for. Then the output signals can be described mathematically as follows [30]:

$$x(\alpha,t) = x_0(t)\sin(2\alpha);\qquad(1)$$

$$y(\alpha,t) = y_0(t)\cos(2\alpha).\qquad(2)$$

If we assume that the amplitudes of both signals are really the same ($x_0=y_0$), since the sensor is integrated on one microcircuit and both bridges are supplied with the same voltage, then the unknown angle α can be determined with high accuracy by signals x and y:

$$\alpha = \frac{1}{2}\arctan\left(\frac{x}{y}\right).\qquad(3)$$

In real practice, the amplitudes of signals x_0 and y_0 will differ. It is explained by the impossibility of achieving the ideal manufacturing accuracy: the accuracy of the sensor installation relative to the axis of rotation of the magnetic field, offset, gain error, temperature and supply voltage fluctuations. In this case, the sine and cosine signals will have an offset of the central axis V_{offset}, Fig.8 [31].

KMZ60 angle-data sensor has a temperature compensation. It can be used to compensate for the effect of decreasing amplitudes as the ambient temperature rises. For the optimal use of the input range of an analog-to-digital converter (ADC), the cosine and sine output voltages are monitored according to the supply voltage. To achieve good signal characteristics, both signals are matched in amplitude and phase. Amplifier bandwidth is sufficient for the low phase delay at maximum specified RPM.
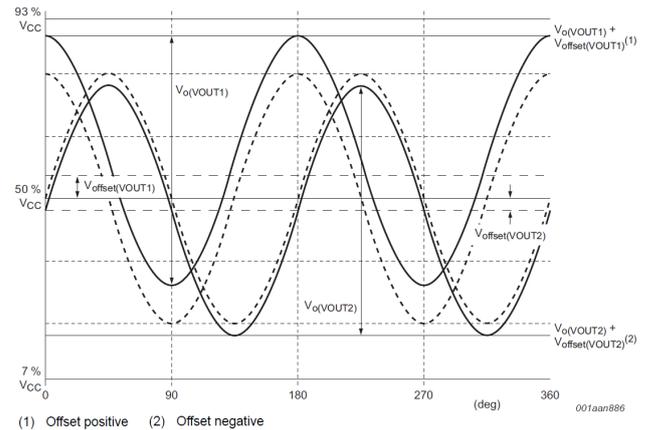

Figure 8. Determination of the amplitude of the output signal and the offset voltage of KMZ60 sensor on exposure to destabilizing factors

The TCC_EN output (Fig. 7) is used to enable temperature compensation. Two modes of temperature compensation of the sensor signal amplitude (TCSSA) are determined. TCSSA is largely compensated by the amplifier if the TCC_EN output is connected to VCC. The amplified sensor signal, which is negatively temperature compensated, is available at the VOUT1 and VOUT2 outputs if the TCC_EN output connected to the ground. The VTEMP output (in both cases) provides a temperature-dependent VO (TEMP) output. The logarithmic value of this voltage is consistent with the supply voltage. It uses an internal PTAT link and can be left unconnected or connected to the ground or to VCC.

The POWERDOWN_EN input pin switches the device to power-down mode and sets the VOUT1 and

VOUT2 outputs to high resistance and turns off the VTEMP output. If not in use, it must be grounded.

To receive the signals from the sensor and process it, it is necessary to use a microcontroller with a high-precision ADC and an internal arithmetic unit for faster execution of trigonometric operations. Therefore, to study the measurement of angular motions using an AMR sensor, a 32-bit STM32F103 microcontroller of the ARM Cortex family was used, that has a 12-bit ADC and an operating frequency of 72 MHz, which fully meets the requirements.

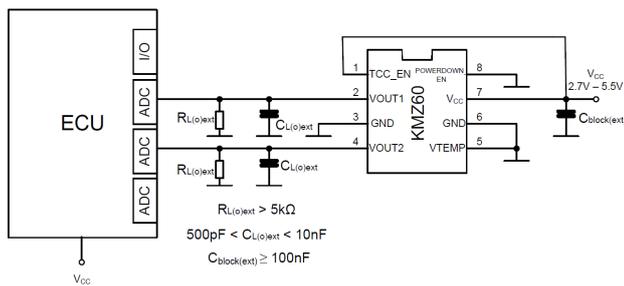The diagram for connecting the sensor to the microconroller (MC) is shown in Fig. 9.

Figure 9. Diagram of connecting the sensor to MC

Taking into account the possible offset of the sensor output signals, the MC must be able to preset in order to
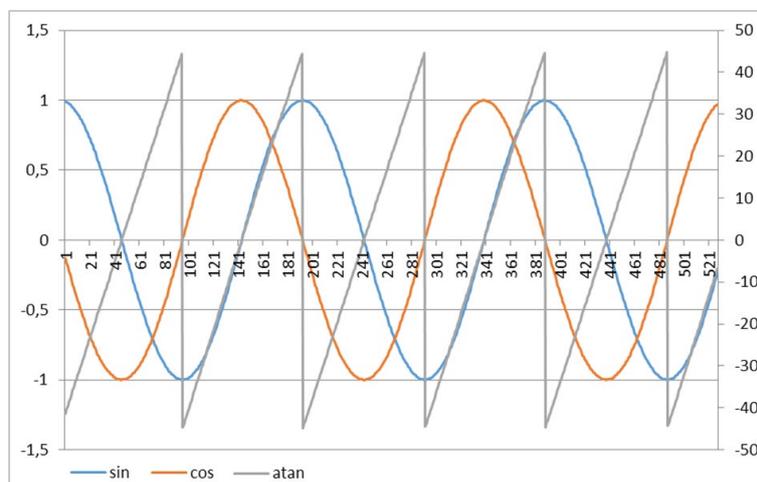
adapt to the measurement conditions. For this, the sensor signal processing program is divided into two modes: calibration and operating mode.

In calibration mode, the magnetic field created by the moving part of the mechanism must make several complete revolutions in order for the sensor to generate several periods of cosine and sine signals. At this stage, the MC determines the minimum U_{min}, maximum U_{max} and middle U_{mid} voltage values for each signal.

In the operating mode, the controller determines the current value of the cosine and sine signal voltages and normalizes the obtained values within [-1...+ 1] according to the formulas:

$$\sin(x) = 2\frac{U_{\sin} - U_{s\,mid}}{U_{s\,max} - U_{s\,min}}; \quad (4)$$

$$\cos(x) = 2\frac{U_{\cos} - U_{c\,mid}}{U_{c\,max} - U_{c\,min}}. \quad (5)$$

Further, by expression (3), the value of the position angle of mechanism α is determined.

The results of measuring the signals of KMZ60 sensor and the angle of the rotary mechanism position according to the above algorithm, with a uniform rotation of the magnetic field, are shown in Fig. 10.

Figure 10. The result of measuring the cosine signals of KMZ60 sensor and the angle of the magnetic field position

As can be seen from Fig. 10, for one full rotation of the rotary mechanism, the cosine and sine signals give two periods, and the received *atan* signal, which has four periods, gives a range of permissible angle measurements from -45° to +45°. That is only 90⁰. For many applications, this range will not be enough.

However, a more detailed analysis of the graphs in Fig. 10 makes it possible to determine that the period of

the *atan* signal corresponds to π/2 of the cosine signal. Thus, analyzing the sign obtained after normalizing the cosine, you can correct the value of angle α by adding +/- 45°.

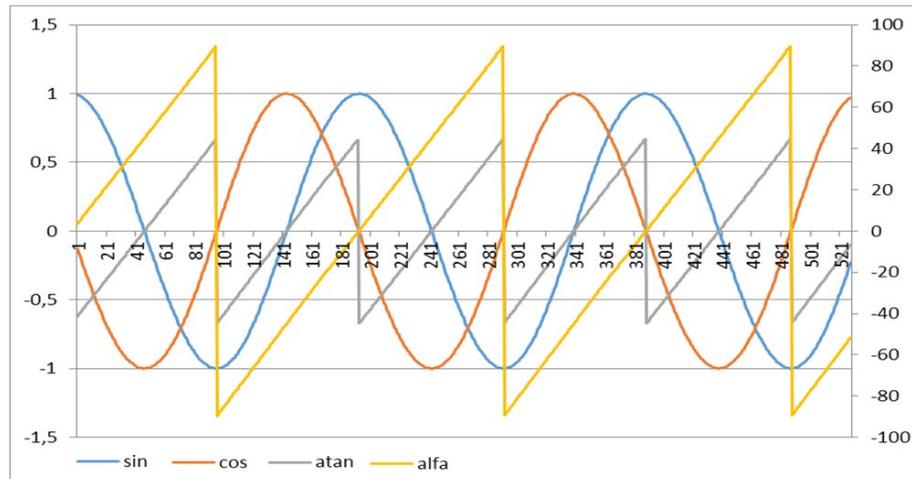The result of measuring the cosine signals of KMZ60 sensor and the angle of the magnetic field in the range -90° ...+ 90 ° is shown in Fig. 11.

Figure 11. The result of measuring the cosine signals of KMZ60 sensor and the angle of the magnetic field position in the range -90°...+90°

The analysis of Fig. 11 allows us to assert that the developed algorithm for processing signals from the AMR sensor helps double the measuring range for the angle of the working mechanism position.

6. Conclusions

Analysis of the methods and devices for determining the angle of the mechanism rotation showed that for automobile purposes the incremental method is the most applicable using:

- a synchronization disc and a digital Hall sensor for mechanisms that make a full rotational movement;
- AMR sensors for mechanisms operating in a limited sector of the rotational angle.

KMZ60 sensor provides two output signals – the sine and cosine signals of the rotational angle of the rotating magnetic field. The output voltage range is proportional to the supply voltage. KMZ60 sensor can operate both in the temperature coefficient compensation mode and in the non-compensated mode.

In addition to the two magnetic field rotational angle signals, KMZ60 sensor provides an output signal that is linear with the internal junction temperature of the IC.

If necessary, KMZ60 can be switched from the Power-Down mode.

An algorithm for processing signals from an AMR sensor has been developed, which enables to double the measuring range for the angle of the working mechanism position.

Conflict of interests.
The authors declare that there is no conflict of interests regarding the publication of this paper.

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