INDUCTIVE ANGULAR ACCELERATION SENSOR FOR AUTOMATIC SPEED CONTROL SYSTEM OF TRAIN TRAFFIC

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Abstract: The article discusses the measurement of motion parameters (displacement, speed, acceleration, sharpness - changes in acceleration and vibration parameters) using a new inductive sensor of angular accelerations of the inertial principle of action with a ferromagnetic liquid and with advanced functionality as well as the analysis of its magnetic circuit and the main technical characteristics.

Keywords: angular acceleration, inductive sensor, ferromagnetic liquid, magnetic circuits, mathematical models, Parametrical Block Diagrams (PBD), characteristics.

Introduction

In the Republic of Uzbekistan, in the context of a globalized economy, an important place is given to the automation of production, including in the field of railway transport. In recent years, systems of automatic control and regulation (SACR) of train speed have been widely used [1]. SACR is designed to automate the management of traffic, to provide them with start-up and dispersal modes of reference, hauls, to sight braking at stations, to collect and to process of traffic information, to function safe, to adhere to schedule accuracy to ±15s, to increase the capacity of suburban areas by about 20%, to reduce the consumption of electricity or fuel for traction approximately 4-5%. Performing all these labor-intensive processes, SACR facilitates the work of the driver, enhances the productivity of locomotive crews and their efficiency, increases the amount of information about the movement of trains and automates the process of documenting the performance of the line [2, 3].

SACR based on various microprocessor means of automation and measuring equipment using a wide range of sensors of electric and non-electric quantities are especially in demand today. In particular, in order to improve the accuracy of train speed control, it is necessary to obtain reliable information about the change in the speed of rotation, i.e. about the angular acceleration of the wheel pairs. Increasing requirements to save energy resources, strict compliance with the schedule of rolling stock movement and increase the efficiency of automation and measuring equipment with the involvement of microprocessor devices determine the need to use primary converters with high sensitivity, accuracy, reliability, extended conversion range and functionality [4].

However, as a comparative analysis has shown, the known mechanical, resistive, piezoelectric, optical and capacitive sensors of angular acceleration satisfy the requirements of the SACR train speed only partially.

Statement of a Problem

In the railway transport, as in other sectors of the national economy, to measure the parameters of motion (displacement, speed, acceleration, sharpness – changes in acceleration and vibration parameters), in particular, to convert the angular acceleration inductive sensors of angular acceleration (ISAA) inertial principle of action began to be used. They are characterized by reliability when working in extreme operating conditions (vibration, temperature fluctuations, dust, pollution, i.e.), simplicity and relative cheapness. Meanwhile, in existing ISAA designs, due to the presence of an air gap between the movable and fixed parts, their sensitivity is relatively low, they are unable to regulate the conversion range. In addition, the limitation of their functionality narrows the scope of their application: they can't be used in the conversion processes of linear acceleration, linear and angular displacement, sharpness, pressure. They can't combine other functions of a technological nature [5]. Due to such serious shortcomings, these sensors can't be used in control systems for various technological processes, in particular in the SACR speed of trains [6, 7, 21]. Therefore, the development of new ISAA designs with high sensitivity, adjustable conversion range and advanced functionality and deep theoretical and experimental research to identify their technical capabilities are actual problems.

The concept of the problem decision

The analysis of the scientific literature testifies to the lack of knowledge of the problem in the field of development and design of ISAA of the inertial principle of action that meet the increased requirements for their search design and the accuracy of calculating magnetic fields in working and non-working gaps. The peculiarity of the problem is that in the studied angular acceleration sensors, the interacting surfaces of the cylindrical body and the inertial element are covered with a ferromagnetic liquid that acts as a thick lubricant and a magnetic conductor. Therefore, the ultimate goal of search design and calculation of the magnetic field of sensors is to select such parameters and geometric dimensions of the magnetic system that will provide optimal characteristics of the ISAA. This problem can be solved only with the use of search design methods and on the basis of accurate knowledge of the law of distribution of the magnetic field in the working and non-working gaps of the studied sensors [8, 9, 23].

A comparative analysis and classification of existing angular acceleration sensors have been conducted. It is revealed that potentiometric sensors have low reliability and a narrow frequency range of measurement (up to 15 Hz); the readings of capacitive sensors are inherently influenced by the temperature, humidity of the environment and extraneous electric fields; piezoelectric sensors have a relatively weak level of the useful signal, a significant error from the nonlinearity of the amplitude characteristic (up to 6%), temperature changes (up to 5%), the cable effect (3 ÷ 10%), the influence of electromagnetic fields (up to 5%). The disadvantages of optoelectronic angular acceleration sensors include the complexity of measuring equipment and range control, instability of characteristics, vibration sensitivity [19, 20, 22]. The advantages of electromagnetic sensors, in particular the ISAA of the inertial principle of action, are justified. It is established that in the existing ISAA under the influence of a constant magnitude of angular acceleration, the movement of the inertial element relative to the body and the appearance of an electric signal at the output of the sensor occur only for a short time. In this case, a small time interval for obtaining information about the change in the angular velocity is a factor that reduces the accuracy of the transformations.

The analysis of the main ratios for the ISAA has established that further research should be directed to the development of new sensor designs with high sensitivity, possible adjustment of the conversion range, as well as to expand their functionality by adapting the sensor not only for the conversion of angular acceleration, but also other non-electrical quantities.

Search design of inductive sensors of angular accelerations is devoted to the improvement of ISAA using methods of scientific and technical creativity, in particular the energy-informational method of search design [8]. The use of this method made it possible to reveal the physical essence of improvements, the regularity of the main directions of ISAA design and facilitated the development of new angular acceleration sensors with the required characteristics. The low efficiency of the known principle of implementation of generalized techniques for improving sensor designs is shown and a new one is proposed: in each row of the matrix of generalized techniques, each new technical solution serves as a prototype of the next one. In this case, the effectiveness of the implementation of generalized techniques increases alongside with the increase in the number of considered pairs of inventions (a pair is an invention and its prototype), i.e. each new design of the ISAA will be more perfect in terms of the improved characteristics and with the increase in the number of implemented generalized techniques, its generalized characteristics as a whole increase significantly. One of the designs developed by ISAA is shown in the Fig.1 [10, 11].

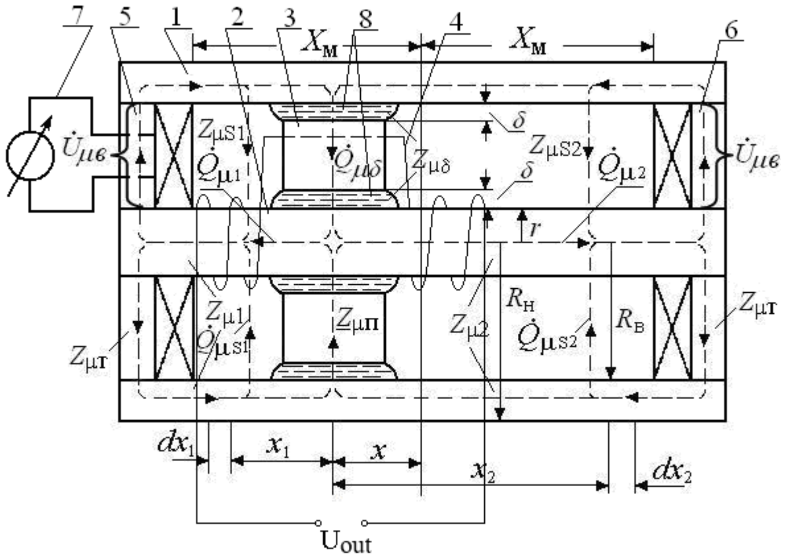

Fig. 1. Inductive sensor of angular acceleration:
1, 2-cylindrical magnetic cores; 3-inertial element-ferromagnetic core; 4-spring-measuring winding; 5, 6-ring electromagnets; 7-adjustable current source; 8-ferromagnetic liquid-grease.

In this sensor design, the viscous friction between the interacting surfaces of the inertial element and the housing is adjusted by changing the current power source (used the phenomenon of the viscosity of ferrofluids under magnetic field). It is shown that using a grease between the interacting surfaces of the inertial element and the housing leads to increased measurement accuracy, and use as a grease ferrofluid allows to increase sensitivity, adjust the range conversion and extend the functionality of the sensor: it can be applied not only to measure angular acceleration, but a linear as well as linear and corner sharpness, pressure.

Analysis of magnetic circuits of the angular acceleration sensor. Expressions for working magnetic flows depending on the longitudinal displacement of the inertial element are determined, taking into account the magnetic resistance of the ferromagnetic liquid and the distributed nature of the magnetic resistance of the steel, as well as the magnetic conductivity of the annular gap between the coaxial magnetic conductors. The influence of the nonlinearity of the main magnetization curve on the flow distribution in magnetic systems is investigated. The issue of optimization of structural and magnetic parameters of the magnetic system of ISAA is considered.

It is admitted that at small values of the thickness of the coaxial cylindrical magnetic cores and the gap between them in comparison with the length of magnetic circuits the magnetic field between plane-parallel magnetic circuits, sources of the magnetic field is identical and create equal magnetic fluxes, and the flux leakage is zero. In addition, it was assumed that the operating range of changes in magnetic flux and voltage in the magnetic circuit corresponds to a linear relationship between the induction and the voltage, which is based on ensuring the appropriate electromagnetic mode of operation of the ISAA.

The calculation of the magnetic circuit of the studied ISAA in the article was made by the method of dividing the chain into certain sections, taking into account the principle of overlap [12].

Determination of the magnetic flux and magnetic voltage generated by the concentrated sections of the excitation winding located at the ends of cylindrical magnetic conductors are made separately for each section. Two sections of the magnetic circuit located on both sides of the inertial element of the sensor are considered (Fig.1). Changes in the magnetic flux and voltage on the elementary sections of the magnetic circuit length, created by the left section of the excitation winding, are equal to [18]:

$$\left.\begin{aligned} d\dot{Q}_{\mu l}(x_1) &= \dot{U}_{\mu l}(x_1) C_{\mu r} dx_1, \\ d\dot{U}_{\mu l}(x_2) &= 2\dot{Q}_{\mu l}(x_1) W_{\mu r} dx_1, \\ -d\dot{Q}_{\mu l}(x_2) &= \dot{U}_{\mu l}(x_2) C_{\mu r} dx_2, \\ -d\dot{U}_{\mu l}(x_2) &= -2\dot{Q}_{\mu l}(x_2) W_{\mu r} dx_2 \end{aligned}\right\}. \tag{1}$$

The solution of the system of differential equations (1) is made taking into account the boundary conditions

$$\left.\begin{aligned} &\dot{U}_{\mu l}(x_1)\Big|_{x_1=0} = \dot{U}_{\mu l}(x_2)\Big|_{x_2=0}, \\ &\dot{U}_{\mu l}(x_1)\Big|_{x_1=0} = \underline{Z}_{\mu r\Sigma}\left[\dot{Q}_{\mu l}(x_1)\Big|_{x_1=0} - \dot{Q}_{\mu l}(x_2)\Big|_{x_2=0}\right], \\ &\dot{U}_{\mu l}(x_1)\Big|_{x_1=X_{\text{M}}-x} = \dot{I}_e w_e - \dot{Q}_{\mu l}(x_1)\Big|_{x_1=X_{\text{M}}-x} \underline{Z}_{\mu \text{T}}, \\ &\dot{U}_{\mu l}(x_2)\Big|_{x_2=X_{\text{M}}+x} = \dot{Q}_{\mu l}(x_2)\Big|_{x_2=X_{\text{M}}+x} \underline{Z}_{\mu \text{T}} \end{aligned}\right\} \tag{2}$$

and has the following form:

$$\dot{Q}_{\mu l}(x_1) = \frac{\dot{I}_e w_e \underline{n}\left[\begin{aligned} &(\underline{m}+1)e^{\underline{\gamma}(X_{\text{M}}+x+x_1)} - \underline{m}\underline{k}e^{-\underline{\gamma}(X_{\text{M}}+x-x_1)} + \\ &+\underline{k}(1-\underline{m})e^{-\underline{\gamma}(X_{\text{M}}+x+x_1)} + \underline{m}e^{\underline{\gamma}(X_{\text{M}}+x-x_1)} \end{aligned}\right]}{e^{2\underline{\gamma}X_{\text{M}}}(\underline{m}+1) - \underline{k}^2(1-\underline{m})e^{-2\underline{\gamma}X_{\text{M}}} - 2\underline{m}\underline{k}ch(\underline{\gamma}x)}, \tag{3}$$

$$\dot{Q}_{\mu l}(x_2) = \frac{\dot{I}_e w_e \underline{n}\left[e^{\underline{\gamma}(X_{\text{M}}+x-x_2)} - \underline{k}e^{-\underline{\gamma}(X_{\text{M}}+x-x_2)}\right]}{e^{2\underline{\gamma}X_{\text{M}}}(\underline{m}+1) - \underline{k}^2(1-\underline{m})e^{-2\underline{\gamma}X_{\text{M}}} - 2\underline{m}\underline{k}ch(\underline{\gamma}x)}. \tag{4}$$

where $\underline{\gamma} = \sqrt{2W_{\mu r}C_{\mu r}}$ - coefficient of distribution of magnetic flux in the magnetic circuit; $C_{\mu r} = \mu_0 \dfrac{\pi(R_i + r)}{R_i - r}$ and $W_{\mu r} = \rho_\mu \dfrac{1}{0{,}5\pi\left(R_o^2 - R_i^2\right) + 0{,}5\pi r^2}$ - running value of magnetic capacity (conductivity) between the cylindrical magnetic cores, and magnetic rigidity (magnetic resistance) of these cores, per unit length of magnetic circuit; $\rho_\mu = \dfrac{1}{\mu\mu_0}$ - the specific magnetic resistance of the magnetic material; μ-magnetic permeability of the magnetic material; $\mu_0 = 4\pi \cdot 10^{-7}$ Н/м - magnetic constant. Here $\underline{m} = \underline{Z}_{\mu r\Sigma}\underline{\gamma} / 2C_{\mu п}$; $\underline{n} = C_{\mu r} / \left(\underline{\gamma} + C_{\mu r}\underline{Z}_{\mu г}\right)$; $\underline{k} = \left(\underline{\gamma} - C_{\mu r}\underline{Z}_{\mu г}\right) / \left(\underline{\gamma} + C_{\mu r}\underline{Z}_{\mu г}\right)$.

Magnetic flows in cylindrical magnetic conductors, created only by the right section of the excitation winding, are found similarly. Let us confine ourselves to the following finite expressions of the working magnetic fluxes created by both sections, which are connected in series and counterclockwise:

$$\dot{Q}_{\mu 1}(x) = \dot{Q}_{\mu l}(x_1) - \dot{Q}_{\mu r}(x_1) =$$
$$= \frac{2I_e w_e \underline{n}\left\{ \underline{m}ch(\underline{\gamma}x_1)\left[e^{\underline{\gamma}(X_\text{м}+x)} - \underline{k}e^{-\underline{\gamma}(X_\text{м}+x)} \right] + sh\underline{\gamma}(x + x_1)\left[e^{\underline{\gamma}X_\text{м}} - \underline{k}e^{-\underline{\gamma}X_\text{м}} \right] \right\}}{e^{2\underline{\gamma}X_\text{м}}(\underline{m}+1) - \underline{k}^2(1-\underline{m})e^{-2\underline{\gamma}X_\text{м}} - 2\underline{m}\underline{k}ch(\underline{\gamma}x)}, \quad (5)$$

$$\dot{Q}_{\mu 2}(x) = \dot{Q}_{\mu l}(x_2) - \dot{Q}_{\mu r}(x_2) =$$
$$= \frac{2I_e w_e \underline{n}\left\{ \underline{m}ch(\underline{\gamma}x_2)\left[\underline{k}e^{-\underline{\gamma}(X_\text{м}-x)} - e^{\underline{\gamma}(X_\text{м}-x)} \right] + sh\underline{\gamma}(x - x_2)\left[e^{\underline{\gamma}X_\text{м}} - \underline{k}e^{-\underline{\gamma}X_\text{м}} \right] \right\}}{e^{2\underline{\gamma}X_\text{м}}(\underline{m}+1) - \underline{k}^2(1-\underline{m})e^{-2\underline{\gamma}X_\text{м}} - 2\underline{m}\underline{k}ch(\underline{\gamma}x)}, \quad (6)$$

In the Fig. 2 shown the curves of the dependence of the working magnetic flows $Q_{\mu 1}(x)$ and $Q_{\mu 2}(x)$, respectively, the deviation of the flow $Q_{\mu 1}(x)$ from its value at $x = 0$, i.e. $\Delta Q_{\mu 1}(x) = Q_{\mu 1}(0) - Q_{\mu 1}(x)$ (Fig.3), as well as the difference of these deviations in both parts of the cylindrical magnetic circuit from the inertial element, i.e. $\delta Q_\mu(x) = \Delta Q_{\mu 1}(x) - \Delta Q_{\mu 2}(x)$ (Fig.4) from the longitudinal displacement x of the inertial element at $\mu = 10^3$ different values of the magnetic permeability μ_l of the ferromagnetic liquid-grease [15].

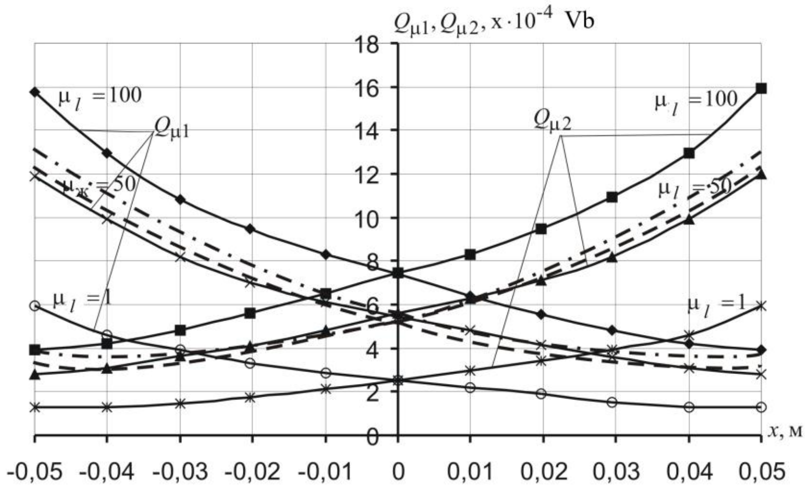

Fig. 2. Curves of changes in working magnetic flows $Q_{\mu1}(x)$ and $Q_{\mu2}(x)$ depending on the longitudinal displacement of the inertial element at different values of the ferromagnetic liquid μ_l : dotted line – experimental data; solid – theoretical data

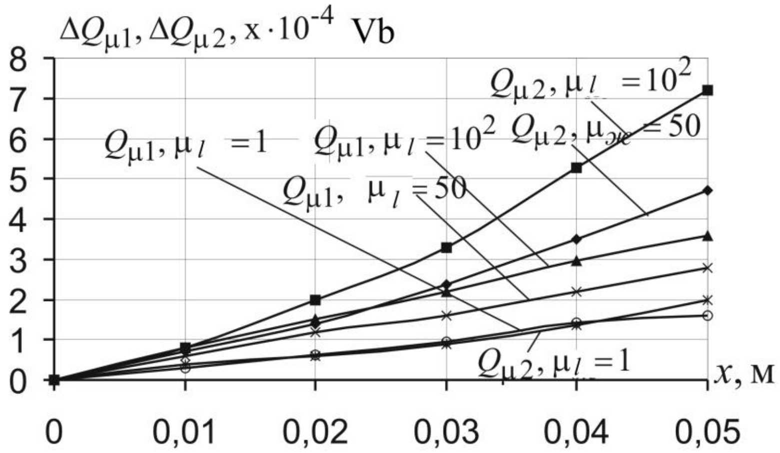

Fig.3. Curves of variation of deviations of working magnetic flows depending on the longitudinal displacement x of the inertial element at different values of the ferromagnetic liquid μ_l .

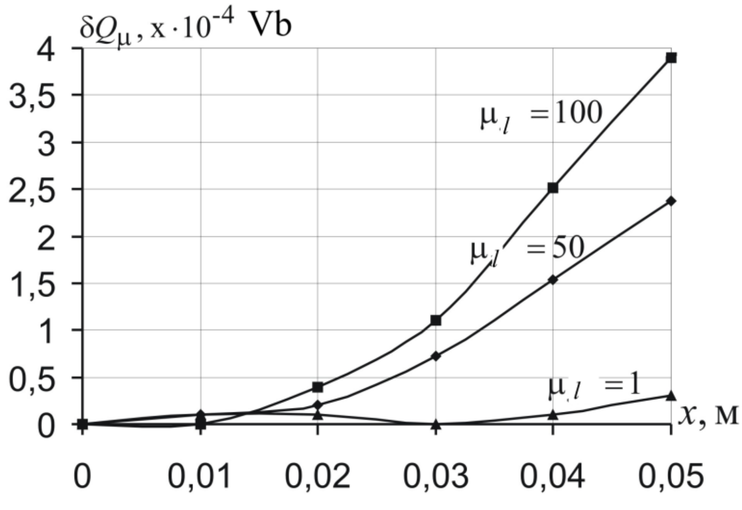

Fig. 4. Curves of change in the difference of deviations of working magnetic flows depending on the longitudinal displacement x of the inertial element at different values of the ferromagnetic liquid μ_l .

The analysis of these curves shows that, increasing μ_l the values of the working magnetic flux of the sensor increased (Fig. 2), deviations of this flux from its values at the position of the inertial element $x=0$ (Fig. 3). In addition, it is found that the longitudinal displacement of the inertial element deflections of the working magnetic flux $\Delta Q_{\mu 1}(x)$ and $\Delta Q_{\mu 2}(x)$ don't change the same. With increase μ_l as the difference between the deviations of the working magnetic flux $\delta Q_{\mu}(x)$ increases too(Fig. 4).

The use of ferromagnetic liquid in the tested sensors of angular acceleration sometimes (especially when the sensor combines the functions of measurements and seals of rotating shafts) leads to a sharp increase in work induction in the circuit to values at which it is impossible to neglect the influence of nonlinear dependencies on the flow $B=f(H)$ distribution in the magnetic system sensor.

In this regard, the characteristic ranges of induction changes in the magnetic circuit are revealed (Fig.5).

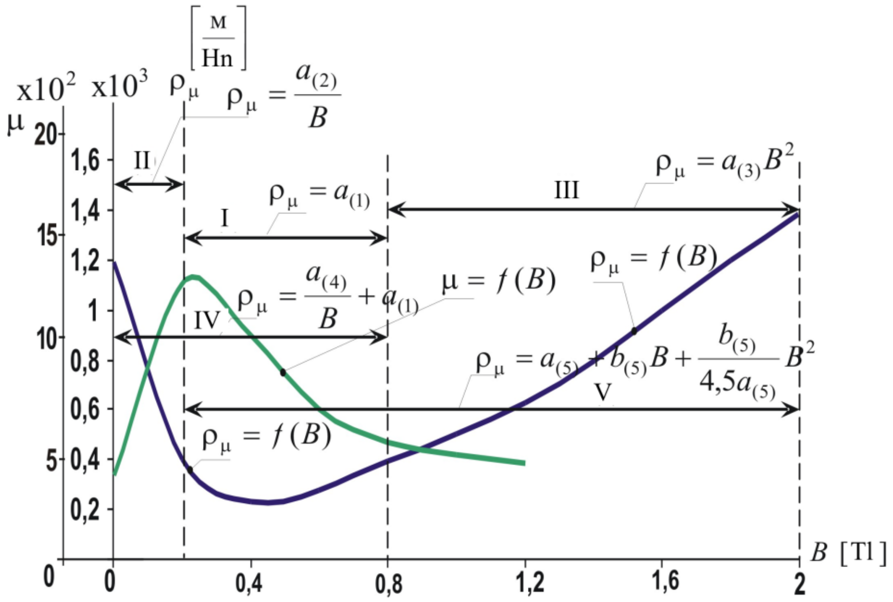

Fig. 5. Curves of dependence of specific magnetic resistance and magnetic permeability of steel from induction

For each range, approximating functions of the dependence of the specific magnetic resistance of steel on induction are proposed and corresponding solutions of nonlinear differential equations are given (Table.1). The maximum discrepancy between the calculated and experimental data is 14.5% [16].

Investigation of the main characteristics of induction angular acceleration sensors.

The resulting expression of the static characteristic has the form

$$E = 2k_1\left[\frac{\gamma}{C_{\mu r}}sh(\gamma x_0) - Z_{\mu\delta}ch(\gamma x_0)\right]sh(\gamma k_2 I'_{aa}), \qquad (7)$$

and in relative units

$$E^{*}=\frac{sh\left(0{,}5\beta I_{\text{aa}}^{'*}\right)}{sh\left(0{,}5\beta\right)}, \qquad (8)$$

where k_1, k_2 - the coefficients of proportionality, x_0 - the minimum value of the x coordinate; $I_{\text{aa}}^{'}$, $I_{\text{aa}}^{'*}=\frac{I_{\text{aa}}^{'}}{I_{\text{aa}\max}^{'}}$ - angular acceleration and its relative value; - the coefficient of attenuation of the magnetic field in the magnetic conductor.

Tabl.1

№	ranges of change B (in the fig.5)	approximating function $\rho_{\text{м}}=f(B)$	differential equation	decision
1	(I)	$\rho_{\mu}=a_{(1)}$	$\dot{Q}_{\mu(1)}^{''}(x)=$ $=2C_{\mu\text{п}}\frac{a_{(1)}}{S_{\mu}}\dot{Q}_{\mu(1)}(x)$	expression (5)
2	(II)	$\rho_{\mu}=\frac{a_{(2)}}{B}$	$\dot{Q}_{\mu(2)}^{''}(x)=$ $=2C_{\mu\text{п}}\frac{a_{(2)}}{BS_{\mu}}\dot{Q}_{\mu(2)}(x)$	$\dot{Q}_{\mu(2)}(x)=$ $=a_{(2)}C_{\mu\text{п}}x^{2}+\underline{A}_{1}x+\underline{A}_{2}$
3	(III)	$\rho_{\mu}=a_{(3)}B^{2}$	$\dot{Q}_{\mu(3)}^{''}(x)=$ $=2C_{\mu\text{п}}\frac{a_{(3)}}{S_{\mu}^{3}}\dot{Q}_{\mu(3)}(x)$	$\dot{Q}_{\mu(3)}(x)=$ $=\sqrt{\frac{S_{\mu}^{3}}{C_{\mu\text{п}}a_{(3)}}\frac{1}{x-\underline{A}}}$
4	(IV)	$\rho_{\mu}=a_{(4)}+b_{(4)}/B$	$\dot{Q}_{\mu(4)}^{''}(x)=\frac{2C_{\mu\text{п}}a_{(3)}}{S_{\mu}}\dot{Q}_{\mu(3)}(x)+$ $+2C_{\mu\text{п}}b_{(3)}$	$\dot{Q}_{\mu(4)}(x)=\underline{A}_{1}e^{\sqrt{2C_{\mu\text{п}}a_{(4)}/S_{\mu}}x}+$ $+\underline{A}_{2}e^{-\sqrt{2C_{\mu\text{п}}a_{(4)}/S_{\mu}}x}-\frac{b_{(4)}}{a_{(4)}}S_{\mu}$
5	(V)	$\rho_{\mu}=a_{(5)}+b_{(5)}B+$ $+\frac{b_{(5)}^{2}}{4{,}5a_{(5)}}B^{2}$	$\dot{Q}_{\mu(5)}^{''}(x)=\frac{2C_{\mu\text{п}}a_{(5)}}{S_{\mu}}\dot{Q}_{\mu(5)}+$ $+\frac{2C_{\mu\text{п}}b_{(5)}}{S_{\mu}^{2}}\dot{Q}_{\mu(5)}^{2}+\frac{2C_{\mu\text{п}}b_{(5)}^{2}}{4{,}5a_{(5)}S_{\mu}^{3}}\dot{Q}_{\mu(5)}^{3}$	$\dot{Q}_{\mu(5)}(x)=$ $=\frac{a_{(5)}}{b_{(5)}}e^{\underline{\gamma}_{(5)}x}\frac{3S_{\mu}}{\underline{A}-e^{\underline{\gamma}_{(5)}x}}$

The degree of non-linearity of the static characteristic of the ISAA is the ratio of the maximum deviation of the ordinate of the considered section of the characteristic from its approximating line to the entire range and is defined as [12, 13]:

$$\varepsilon=\frac{[0{,}5E^{*}(I_{\text{aa}}^{'*}=1)-E^{*}(I_{\text{aa}}^{'*}=0{,}5)]}{2E^{*}(I_{\text{aa}}^{'*}=1)}\cdot100\%=\left[0{,}25-0{,}5\frac{sh(0{,}25\beta)}{sh(0{,}5\beta)}\right]\cdot100\%. \qquad (9)$$

On the basis of the developed mathematical model, of the ISAA constructed the static characteristics, and the factors affecting the static characteristic and the degree of its nonlinearity are studied (Fig. 6 and 7).

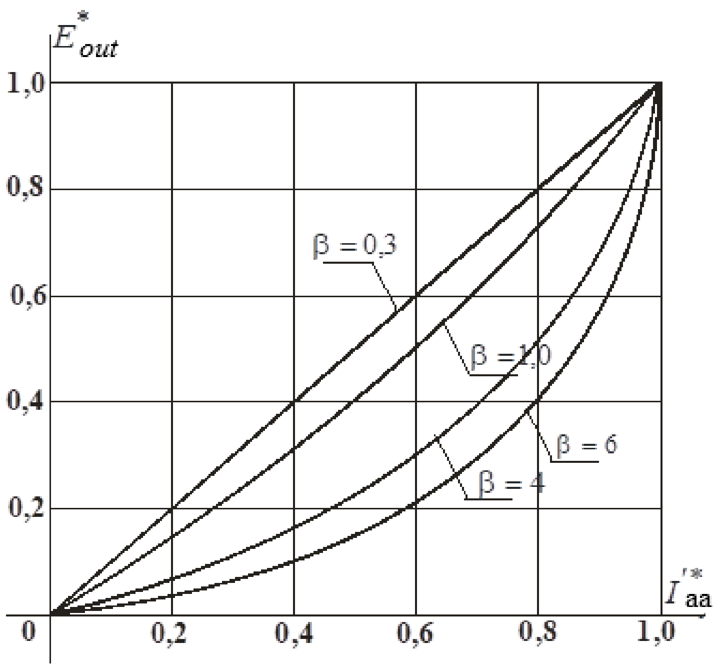

Fig.6. Curves of the static characteristics of ISAA

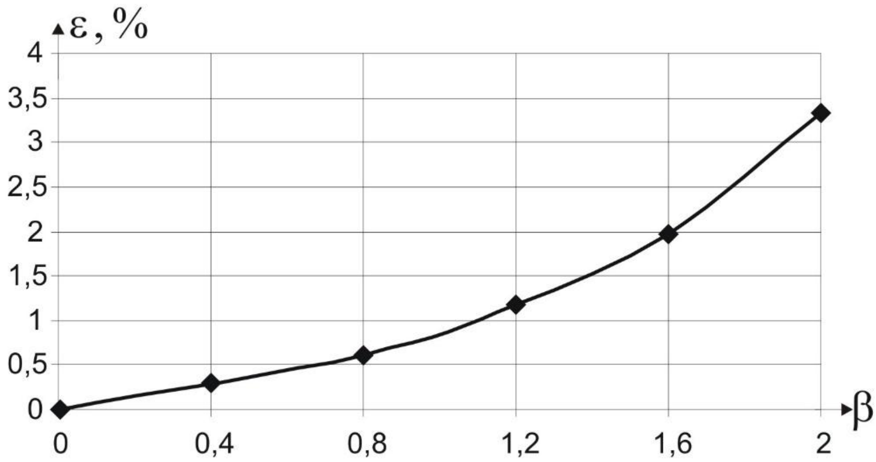

Fig.7 The curve of the dependence of the degree of nonlinearity of the static characteristic on the coefficient β

Analysis of these characteristics of the studied sensors shows that with increasing β (elongation or reduction of the cross section of cylindrical magnetic conductors), the nonlinearity of the static characteristic increases too. The change in the magnetic permeability of the ferromagnetic liquid leads to a proportional change in the sensitivity, while the degree of nonlinearity of the static characteristic of the sensor practically doesn't change at all.

The dynamic characteristics of the ISAA were studied at linearly increasing and sinusoidally changing angular accelerations. For the first mode, the output signal expression is obtained as [14, 17]

$$e = E_{1m} \sin \omega t + E_{2m} \cos \omega t - E_{3m} \cos \omega t = e_1 + e_2 + e_3. \quad (10)$$

Based on the analysis of expression (10) and curves (Fig. 8) it is established that its first component is a generator EMF proportional to the rate of change in angular acceleration. The last two components are transformer: the second component (due to the smallness of the graph, it is increased in comparison with the other 10 times) is proportional to the rate of change in angular acceleration and increases in time with a constant speed, and the third is proportional to the speed of rotation of the inertial element and the damping coefficient.

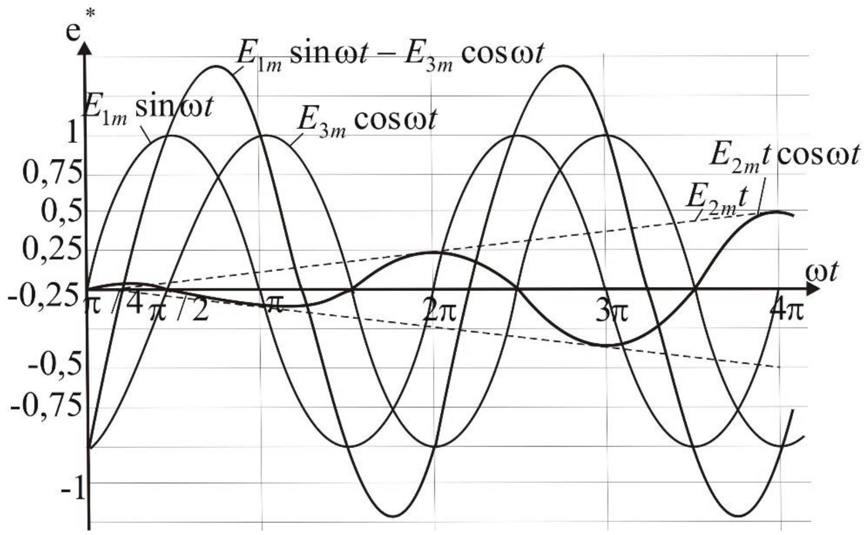

Fig. 10. Curves of changes in the output signal over time and their components

In another dynamic mode, the output signal of the sensor has four components, the amplitudes of two of which are modulated by the sinusoidal, and the other two – by the cosine law.

The transient characteristic of the developed sensor at linearly increasing angular accelerations has the following form:

$$U_{\text{эг}}(t) = \frac{K_{\text{г}}}{\omega_{\text{му}}^2}t + \frac{K_{\text{г}}e^{-\delta t}}{2\omega_{\text{му}}^4\sqrt{\delta^2-\omega_{\text{му}}^2}}\left[\left(-\delta-\sqrt{\delta^2-\omega_{\text{му}}^2}\right)^2 e^{\sqrt{\delta^2-\omega_{\text{му}}^2}\,t} - \right.$$
$$\left. -\left(-\delta+\sqrt{\delta^2-\omega_{\text{му}}^2}\right)^2 e^{-\sqrt{\delta^2-\omega_{\text{му}}^2}\,t}\right] - \frac{K_{\text{г}}\delta}{\omega_{\text{му}}^4}, \qquad (11)$$

where K_{Γ} - the coefficient of proportionality; δ - the coefficient of attenuation and $\omega_{\text{му}}$ - the angular frequency of the mechanical oscillatory system of the sensor.

It is established that at $t = 0$ and $t = \infty$ the free component of the transition process in the mechanical circuit of the sensor is zero. Increasing the viscosity of the ferromagnetic liquid under the influence of a magnetic field allows you to increase the time of exposure to the force due to angular acceleration.

The analysis of the work of the studied sensors and their characteristics showed that possible sources of errors are imperfection of the method, the principle of operation, inaccuracy of manufacture, instability of the power supply, unfavorable external conditions. Their classification is made, according to which the first three are the sources of the main error, and the rest are the sources of additional error. To identify the sources of errors and their analysis, the well-known concepts are used of additive and multiplicative errors.

It is shown that the use of a ferromagnetic liquid as a thick grease between the interacting surfaces of the housing and the inertial element with a large value μ_l reduces the measurement error from the transverse backlash of the inertial element (Fig.12).

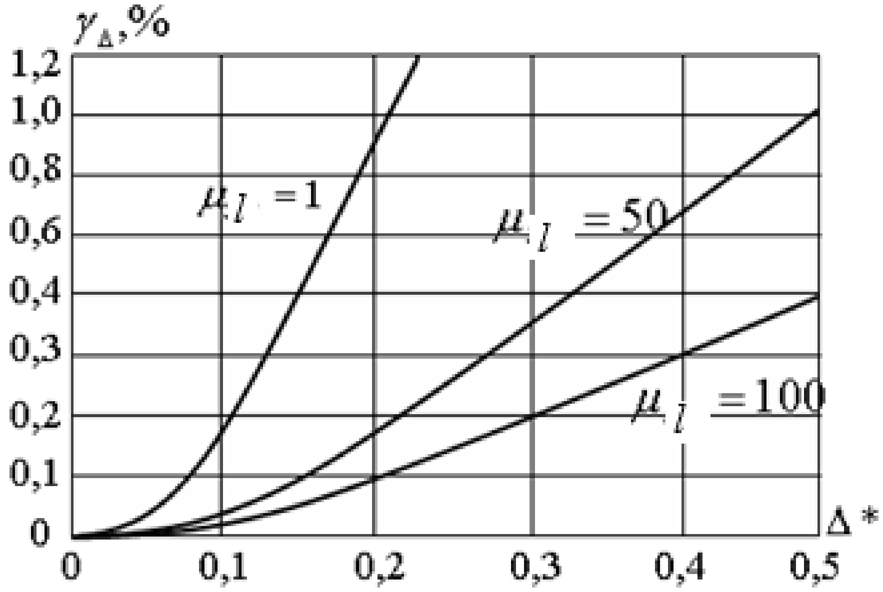

Fig.12. Errors of the ISAA depending on the transverse backlash of the inertial element at different values

The quantitative assessment of the errors showed that the maximum reduced error doesn't exceed 1.5% for the permissible values of temperature and excitation current deviations.

Conclusion

1. It is shown that using a thick grease between the interacting surfaces of the inertial element and the housing leads to increased measurement accuracy, and use as a grease ferromagnetic liquid allows to increase sensitivity, adjust the range conversion and extend the functionality of the sensor: it can be applied to measure not only the angular, but linear acceleration, linear and angular sharpness, pressure, and also can combine the function of the seal rotating shafts.

2. The analysis of magnetic circuits developed ISAA showed that with increasing magnetic permeability μ_l of the ferromagnetic liquid, the values of the working magnetic flows and the deviations of these flows from the values at the central position of the inertial element increase. It is established that the longitudinal displacement of the inertial element leads to a disproportionate change in the working magnetic flux, respectively in the left and right parts of the inertial element of the magnetic system.

3. The study of the influence of the nonlinearity of the main magnetization curve on the flow distribution in magnetic systems of angular acceleration sensors revealed the characteristic ranges of induction changes in the magnetic circuit. For each range, approximating functions of the dependence of the specific magnetic resistance on the induction are proposed, and corresponding solutions of nonlinear differential equations are given. It was found that the maximum discrepancy between the theoretical and experimental results does not exceed 14.5%.

4. It has been found that with an increase in the attenuation coefficient of the magnetic field in the magnetic conductor (β), the degree of nonlinearity of the static characteristic (ε) increases (for example, at $\beta = 1$ and $\beta = 6$, ε = 0.96% and ε = 14.5%), and the change has virtually no effect on μ_l. It is shown that sinusoidal change in the angular acceleration sensor output has four components, two of which are amplitude modulated sine and the other

cosine laws. It is established that an increase in the working magnetic flux leads to a reduction in the transition time.

5. It is revealed that the main sources of possible errors of ISAA are inaccuracy of manufacture, instability of the excitation current and external conditions. Based on the analysis of the obtained analytical expressions of errors, it is found that the accuracy of the developed ISAA is most affected by fluctuations in the amplitude of the excitation current and the ambient temperature. In this case, the maximum reduced error does not exceed 1.5%. It is shown that the use of a ferromagnetic liquid with a large μ_l value as a thick grease between the interacting surfaces of the housing and the inertial element reduces the measurement error from the transverse backlash of the inertial element (for example $\Delta^* = 0{,}2$, $\mu_l = 1$, and $\mu_l = 10^2$ the error values are 0.85 and 0.1%, respectively).

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