Calculation of magnetic systems of speed and gear teeth integrity sensors

Vladimir Bezkorovaynyy, S. Boureima, Dmitry Serhienko

Volodymyr Dahl East-Ukrainian National University, Lugansk, Ukraine

S u m m a r y. Magnetic system of speed and integrity of teeth sensors, which is a U-shaped magnetic core and magnetic circuit of circular section is optimized. A mathematical model of the dependence of the magnetic flux in the core induced by magnetized gear is presented. The results of numerical experiment are given. The conclusions and recommendations for optimizing the parameters of the SS magnetic systems are made
K e y w o r d s. Magnetic system, optimization, gear, mathematical model.

INTRODUCTION

Actuality of the study. Speed sensor (SS) are the most common elements of control systems.

Magnetic transducers of SS due to high sensitivity, the mechanical strength, the ability to operate in a contaminated environment, temperature stability have advantages over SS using another principle.

Improving the efficiency of magnetic SS is possible on the basis of theoretical studies of the magnetic system. The optimal parameters of the magnetic systems of SS are connected to the module gear, the frequency of which is controlled [1].

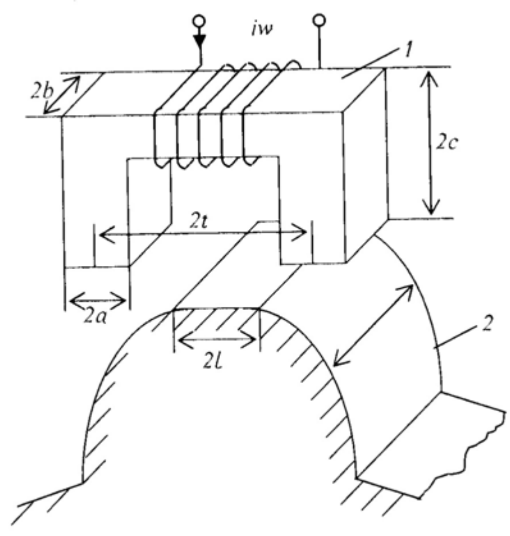
The basis of theoretical and mathematical model of optimization is the research of the magnetic field in the work area of SS. Responding to the irregular geometrical shape of the magnetic system of SS, which includes gear, there must be some idealization of form of ferromagnetic parts, which will provide analytical dependences for the basic value of the magnetic flux in the magnetic core of SS.

Feature of the magnetic system is that it consists of a magnetic transducer, the parameters of which are manageable and gear with given geometrical parameters

The purpose of article is to describe the method of calculation of the theoretical and parametric optimization of SS with U-shaped and cylindrical magnetic system

MATERIALS AND RESEARCH RESULTS

Magnetic system of SS, which is U-shaped magnetic core, that contains winding or magnetically sensitive element - Hall probe or flux gate is considered (fig. 1).



1 – magnetic core, 2 – gear tooth

Fig. 1. The magnetic system of SS

Effectiveness of SS with U-shaped and cylindrical magnetic system means the ratio

$$\varepsilon = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}}, \quad (1)$$

where: Φ_{max}, Φ_{min} is maximum and minimum values of the magnetic flux in the ferromagnetic core at its certain position relative to the tooth.

The criterion of optimization of the magnetic system is to obtain the maximum value $K_{эф} = K_{эф\,max}$.

To determine the main regularities of development of the information magnetic flux in the magnetic core of the sensor, the following idealized geometric model of the magnetic system is proposed (fig. 2).

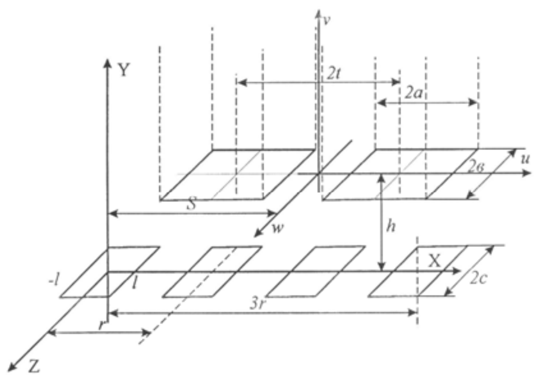


Fig. 2. The geometric model of the magnetic system of U-shaped sensor.

The basis of the calculation of the magnetic flux in the magnetic core is the K.M.Polivanov`s theorem of reciprocity, which is converted to the following form

$$\Phi = \frac{\mu_0}{iw} \int_{S_\Phi} \varphi_M \bar{M}_n dS_\Phi, \quad (2)$$

where: iw – ampere-turns of coil located at the core;

$\bar{M}_n$ – normal component of the magnetization on the surface of a ferromagnetic body;

S_Φ – surface area of a ferromagnetic body;

φ_M – scalar magnetic potential generated by core with winding placed on it with the number of turns w.

It is proposed to calculate the value φ_M by the formula

$$\varphi_M = \frac{1}{4\pi} \int_{S_n} \frac{\sigma}{r_{PQ}} dS_\Phi, \quad (3)$$

where: σ – density of a simple layer of fictitious magnetic charges at the poles of U-shaped core;

r_{PQ} – vector drawn from the source point P to the observation point Q.

In the first approximation we can assume that the normal component of the magnetization M_n is constant throughout the site with an area of the tooth *4ls*. This magnetization is close to the real, if gear magnetized with permanent magnet. We can assume that

$$M_n = (\mu - 1) H_{0n}, \quad (4)$$

where: H_{0n} – normal component of the magnetization field intensity;

μ – relative magnetic permeability of the ferromagnetic material.

Then (2) can be rewritten as

$$\Phi = \frac{\mu_0 (\mu - 1)}{iw} \int_{S_\Phi} \varphi_M H_{0n} dS, \quad (5)$$

where: H_{0n} – normal component of the magnetization field intensity on the surface of a ferromagnetic body.

It is assumed that the coil creates a current at the poles of the measuring transducer core constant density of magnetic charges: at one pole σ, on other $-\sigma$.

The potential created by a magnetic core with winding placed on it with the current, creates MDS - iw, is equal

$$\varphi_M = \varphi_{1M} + \varphi_{2M} = \frac{1}{4\pi} \int_{S_П} \frac{\sigma dS}{R_1} - \frac{1}{4\pi} \int_{S_П} \frac{\sigma dS}{R_2}, \quad (6)$$

where:

$R_1 = \sqrt{(x-t-u)^2 + h^2 + w^2}$; $R_2 = \sqrt{(x+t-u)^2 + h^2 + w^2}$;

values of t, u, w, x are clear from fig. 2.

Value $\sigma = \frac{iw}{2h}$, assuming that the magnetic voltage drop occurs in air gap of measurement transducer.

With (5) and (6)

$$\Phi = \frac{(\mu-1) H_{0n} b \mu_0}{4\pi h} \sum_{i=-2}^{2} \int_{-c}^{c} \int_{l-ir}^{l+ir} \left(\int_{-b}^{b} ln \frac{x-t-a+S+\sqrt{(x-t-a+S)^2 + h^2 + (z-w)^2}}{x-t+a+S+\sqrt{(x-t+a+S)^2 + h^2 + (z-w)^2}} dw - \right. \quad (7)$$

$$- \int_{-b}^{b} ln \frac{x+t-a+S+}{x+t+a+S+}$$

$$\left.\frac{+\sqrt{(x+t-a+S)^2+h^2+(z-w)^2}}{+\sqrt{(x-t+a+S)^2+h^2+(z-w)^2}}dw\right)dxdz.$$

The aim of numerical calculations is to determine the dependence of the magnetic flux Φ on the parameters of the magnetic system of the measurement transducer. The values entering the formula (7), normalized by modulus of gear

$$a^*=\frac{a}{m},\ b^*=\frac{b}{m},\ c^*=\frac{c}{m},\ r^*=\frac{r}{m},\ t^*=\frac{t}{m},$$
$$S^*=\frac{S}{m},\ h^*=\frac{h}{m},\ M^*=\frac{M}{m}.$$

The minimum value of h is chosen so that the air gap between the plane of the poles of the magnetic system and the surface was not less than the value of the beats $h_{min}=\Delta h$.

In the numerical experiment, parameters a, t, h are changed (the asterisks are omitted). The value of S is chosen from the two values, one value corresponds to the maximum flow in the magnetic measuring transducer S_{max}, second - S_{min}. The magnetic flux in the magnetic system is directly proportional to the values of b and c, so that these values being calculated are not changed. The gap between the side walls of a U-shaped magnetic core is referred to as $g=2(t-a)$. The value of r is fixed. Tables 1 and 2 show the data of numerical experiment on the calculation efficiency ratio of the magnetic system of SS with rectangular section of magnetic circuit.

Table 1. The values of the efficiency coefficient of the SS magnetic system ε with h=0,1; $m=8$

Variants / Parameters	1		3	4	5
$2a$	1,6	1,6	1,6	1,6	1,6
$2t$	2	2,4	2,8	3,2	3,6
g	0,4	0,8	1,2	1,6	2,0
ε, short-cut calculation	0,4	0,52	0,68	0,56	0,41

The value of the length of a gear area is chosen equal $2l = 1$, the air gap between areas is also $2l$.

Numerical results shown in tables 1 and 2 show that there is a distinct maximum effectiveness ratio of the magnetic system of SS with the air gap between the poles of an approximately equal $2b$. When changing the air gap between the poles of the next higher efficiency ratio will fall more slowly than when changing gap size g down. By increasing the air gap h SS efficiency ratio decreases, but the values of the optimal parameters *2a, 2t, g* remain unchanged.

Table 2. The values of the efficiency coefficient of the SS magnetic system ε with h=0,2; $m=8$

Variants / Parameters	1	2	3	4	5
$2a$	1,6	1,6	1,6	1,6	1,6
$2t$	2	2,4	2,8	3,2	3,6
g	0,4	0,8	1,2	1,6	2,0
ε, short-cut calculation	0,16	0,22	0,34	0,29	0,26

In optimizing control parameters are 2a, 2t. Their values should ensure the maximum efficiency ratio, or the minimum value of the function G=1-ε. Minimization of function G is carried out by coordinatewise descent.

In the present case besides the parameters *2a* and *2t* the parameters S_{max} and S_{min} are taken into account for which the value of the flux in the core has a maximum and minimum values. In optimizing initially these parameters are searched from the values of the magnetic flux, and then the optimal values of *2a* and *2t* are searched. After determining the optimal values of *2a* and *2t* may be that the values S_{max} and S_{min} have changed. Then for the optimal parameters *2a* and *2t* once again S_{max} and S_{min} are defined and the process of coordinatewise descent is repeated again to find new optimal values of *2a* and *2t.*

The results of optimization of parameters of the SS magnetic system illustrated by the data given in table 3.

Table 3. Optimization of the parameters of the magnetic system

Parameters / Step number	S_{max}	S_{min}	$2a$	$2t$	ε
Initial settings	0	0,92	1,4	3,6	0,54
The value of the parameters $k=1$	0,02	1,04	1,58	2,9	0,61
The value of the parameters $k=2$	0,01	1,02	1,62	2,85	0,66
The value of the parameters $k=3$	0,015	1,02	1,65	2,83	0,69

Calculations are made with $h=0,2$. From the data in Table 3 it is clear that after each refinement of values S_{max} and S_{min} an increase effectiveness ratio ε occurs, until it reaches its maximum value.

We consider a cylindrical magnetic system of SS containing magnetically sensitive element - the Hall probe (fig. 3).

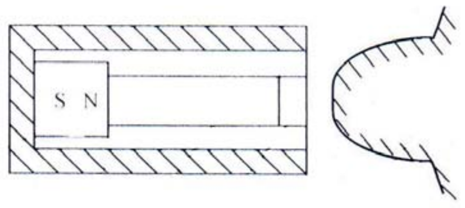


Fig. 3. SS simplified design with a cylindrical magnetic system.

Effectiveness of this type of speed sensor, means the ratio of (1), the same as for SS with U-shaped magnetic system

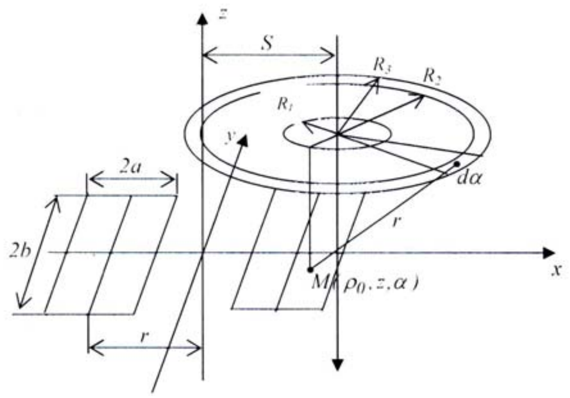


Fig.4. The geometric model of a magnetic system with a cylindrical core.

Let the inner core of the magnetic system has the magnetization M_{n0}, and the outer cylinder $-M_{n0}$, created by winding with a current iw, located on the inner core and the values of these values will be determined further. The potential created by terminal and internal disks can be calculated by the following formula:

$$\varphi = \frac{M_{n0}}{4\pi}\int_0^{2\pi}\int_0^{R_1}\frac{\rho d\alpha d\rho}{\sqrt{z^2+\rho_0^2+\rho^2+2\rho\rho_0\cos\alpha}} - \frac{M_{n0}}{4\pi}\int_0^{2\pi}\int_{R_2}^{R_3}\frac{\rho d\alpha d\rho}{\sqrt{z^2+\rho_0^2+\rho^2+2\rho\rho_0\cos\alpha}}. \quad (8)$$

The magnetic flux in the core of the magnetic circuit is calculated using the K.M.Polivanov`s reciprocity theorem, which is shown in equation (2).

It can be assumed that the normal component of the magnetization M_n is constant throughout area of the tooth. Using (5) and (8) we can write

$$\Phi = \frac{\mu_0(\mu-1)}{iw}\int_{-a}^{a}\int_{-b}^{b}H_n \cdot \left[\int_0^{2\pi}\int_0^{R_1}\frac{\rho d\alpha d\rho}{\sqrt{h^2+(x-S)^2+y^2+2\rho\sqrt{x^2+y^2}\cos\alpha}} - \int_0^{2\pi}\int_{R_2}^{R_3}\frac{\rho d\alpha d\rho}{\sqrt{h^2+(x-S)^2+y^2+2\rho\sqrt{x^2+y^2}\cos\alpha}}\right]. \quad (9)$$

Equation (9) is used in numerical experiments to determine the dependence of the efficiency coefficient of the magnetic system on the parameters R_1, R_2, R_3. The values entering the formula (9), normalized by value of the gear module

$$R_1^* = \frac{R_1}{m},\ R_2^* = \frac{R_2}{m},\ R_3^* = \frac{R_3}{m},\ S^* = \frac{S}{m},\ h^* = \frac{h}{m}.$$

Further asterisks of the letters that represent referred values, not put

In calculation the parameters $h, R_1, R_2, \Delta R = R_3 - R_2$. are changed. Value of the magnetic flux in the core of measuring transducer is determined at two points relative to movement of the magnetic system of SS and gear teeth: at point, where $\Phi = \Phi_{max}$ and at point, where $\Phi = \Phi_{min}$. The value of r is fixed. Platform length $2a = l$, the value of the air gap $h = 0,2$.

In tables 1, 2, 3, data of numerical experiment on the calculation of efficiency ratio of the SS magnetic system with a round section of magnetic circuit are given.

In optimizing controlled parameters are $R_1, \Delta R, R_3$; their optimal values should ensure the maximum efficiency ratio ε or the minimum value of the function $G=1-\varepsilon$. Minimization of function G is carried out by coordinatewise descent. Besides the parameters $R_1, \Delta R, R_3$, the parameters S_{max} and S_{min} are taken into account in which the flow value reaches its maximum and minimum values.

Table 4. The dependence of the efficiency of the value of R_3

Parameters \ Variants	1	2	3	4	5
R_3	1,2	1,3	1,4	1,5	1,6
R_1	0,74	0,74	0,74	0,74	0,74
ΔR	0,2	0,2	0,2	0,2	0,2
ε	0,38	0,4	0,38	0,36	0,28

Table 5. The dependence of the efficiency of the value of R_1

Parameters \ Variants	1	2	3	4	5
R_1	0,4	0,45	0,5	0,55	0,6
R_2	1,3	1,3	1,3	1,3	1,3
ΔR	0,2	0,2	0,2	0,2	0,2
ε	0,3	0,36	0,42	0,44	0,38

Optimization of SS with cylindrical magnetic system is the same as an optimization of SS with U-shaped magnet system.

Results of optimization of parameters of SS with cylindrical magnetic system are shown in table 6. The data in Table 6 indicate that all values converge to certain values that are optimal

Table 6. Optimization of the parameters of the magnetic system

Step number \ Parameters	S_{max}	S_{min}	R_1	ΔR	R_3	ε
Initial settings	0	0,95	0,38	0,25	1,36	0,36
The value of the parameters $k = 1$	0,04	1,02	0,45	0,27	1,38	0,39
The value of the parameters $k = 2$	0,02	1,01	0,48	0,28	1,41	0,41
The value of the parameters $k = 3$	0,03	1,01	0,51	0,28	1,42	0,42
The value of the parameters $k = 4$	0,025	1,01	0,51	0,28	1,42	0,42

CONCLUSIONS

1. In optimizing parameters of SS with U-shaped and cylindrical magnetic system maximum and minimum points of the magnetic flux can shift, which requires an adjustment of their position followed by repeat of the optimization procedure
2. Optimal parameters of the magnetic system of SS with U-shaped magnetic core of rectangular sections are length of poles $2a = 1,62$ m and the distance between the poles of the core $2t = 2,85$ m.
3. Optimal parameters of the magnetic system of SS with a cylindrical magnetic core are round inner core radius is $R_1=0,51m$, thickness of the outer cylinder $\Delta R=0,28m$, the value of the radius of magnetic system $R_3=1,42m$.

REFERENCES

1. **Afanasiev Yu.V., 1989.:** Ferroprobes, Moscow, Energy, - 156 p.
2. **Afanasiev Yu.V., 1986.:** Fluxgate devices, Leningrad, Energoatomizdat, - 186 p.
3. **Boukreev V.V., 2004.:** By choosing the size of the measurement sensors ferromodulyatsionnyh inhomogeneous magnetic fields. Proceedings of Donetsk National Technical University. Series: "Electrical and Power Issue 79, Donetsk SHEE" DNTU "
4. **Buhl V.K. Ionak V.F. Dubenets A.L., 1972.:** Circular toothed magnetoelectric sensors // Instruments and Control Systems, - № 2. - p. 33-34.
5. **Chaban V.I. Semenov S.T., 1981.:** Refined mathematical model of the induction sensor angular speed, Theoretical Electrical Engineering: Collection, Lviv. No. 30, - S. 79-82.
6. **Domashevsky B.N., Kolikhanov V.K., Simonov N.B., 1983.:** Fluxgate flaw MFD-4K, Defectoscopy, - № 6, - p.43-47.
7. **Kolchin A.B., 1984.:** Sensor for diagnostics of machines, Moscow, Mechanical Engineering, -116p.
8. **Kolikhanov V.K., Gritsenko A.C., Domashevsky B.M., 1984.:** Installation for fluxgate of weld joints, Defectoscopy, - № 2. - P.31-35
9. **Kolikhanov V.K., Gritsenko A.C., Simonov N.B., 1986.:** On Improving of equipment for fluxgate-tight control panel, Defectoscopy, - № 7 - S. 90-91.
10. **Konyukhov N.E., 1987.:** Electromagnetic sensors of mechanical quantities, Moscow, Engineering. -255p.
11. **Kurbatov PA, Arinchin S.A., 1984.:** The numerical calculation of electromagnetic fields, Moscow, Energoatomizdat, -167 p.
12. **Lisitskaya L.N., Shumkov J.M., 1984.:** Transient electromagnetic field in the exciting coil - a plate under pulsed excitation, Theoretical Electrical Engineering, - № 37. - S. 125-134.
13. **Mikhlin S.G., Smolitskii H.L., 1965.:** Approximate methods for calculating differential and integral equations – Moscow, Science, - p. 55-69.
14. **Miroshnikov Vadim, Tatyana Pobeda, Sergey Kostin, 2010.:** Calculation of quantity characteristics of the field created by local magnetizing devises. TEKA Commission of Motorization and Power Industry in Agriculture, XC, p. 190-197.
15. **Miroshnikov Vadim, Oleivi Anver, 2010.:** Theoretical analysis of a circle current converter operation under control of hollow cylinders. TEKA Commission of Motorization and Power Industry in Agriculture, XB, p. 33-42.
16. **Nikitenko A.G., Grinchenko V.P., Bakhvalov Yu.A.** Calculation of magnetic fields and integral characteristics of electromagnets with unclosed magnetic circuit. - Electromechanics, № 10, 1977, p. 1067-1072.
17. **Romanenko A.B., 2003.:** Analysis and synthesis of magnetic systems, linear encoders Dissertation for the degree. Candidate. tech. of Sciences, Kiev, - 219 p.
18. **Yakovenko V.V., 1989.:** Magnetic sensors control systems based on ferromodulyatsionnyh elements: Abstract. Dis. Doctor. tech. Science. - Kharkov, – 34p.

19. **Yakovenko V.V., 1989.:** Magnetic sensors of mechanical quantities, Sensors and techniques to improve their accuracy: Study Guide - Kiev, Graduate School, - S. 57-109.
20. **Yoshino I., Ao K., Kato M., Mizutani S., 1987.:** MRE rotation sensor: high-accuracy, high-sensitivity magnetic sensor for automatic use "SAE Iechn. Pap. Jer." - №870470. - P.67-73.
21. **Zagidullin R.V., 2007.:** Calculation of the residual magnetization of the deformed steel plate, Ufa, Bashkir University Bulletin, – 14 p.

К РАСЧЕТУ МАГНИТНЫХ СИСТЕМ ДАТЧИКОВ ЧАСТОТЫ ВРАЩЕНИЯ И ЦЕЛОСТНОСТИ ЗУБЬЕВ ШЕСТЕРНИ.

Владимир Безкоровайный, Сейбу Бурейма, Дмитрий Сергиенко

Аннотация. Оптимизируется магнитная система датчиков частоты вращения и целостности зубьев, представляющая собой П-образный магнитопровод и магнитопровод круглого сечения. Представлена математическая модель зависимости магнитного потока в сердечнике, индуцированного намагниченным зубчатым колесом. Приведены результаты численного эксперимента. Сделаны выводы и даны рекомендации по оптимизации параметров магнитных систем ДЧВ.

Ключевые слова. Магнитная система, оптимизация, шестерня, математическая модель