SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Semarak Engineering Journal

Journal homepage:
https://semarakilmu.com.my/journals/index.php/sem_eng/index
ISSN: 3036-0145

Resonance Sensors of Motion Parameters

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ARTICLE INFO

Article history:
Received 9 January 2024
Received in revised form 18 February 2024
Accepted 22 March 2024
Available online 30 May 2024

Keywords:
Electromagnetic resonant sensor of motion parameters; linear movement; linear speed; voltage resonance; magnetic flux; magnetomotive force; magnetic conductivity; transformer; moving measuring winding; generator emf; sensitivity

ABSTRACT

The article studies the design features of known and developed electromagnetic resonant sensors of motion parameters and develops their mathematical models, which make it possible to study the main technical characteristics of these sensors. A comparative analysis of the obtained expressions of the output signals and the sensitivity of the known and proposed electromagnetic resonant sensors of motion parameters shows that the sensitivity of the proposed sensor due to the implementation of each magnetic field source in the form of a multi-turn magnetic circuit with an excitation winding section, the turns of which cover all turns of the multi-turn magnetic circuit, in w_m (where w_m- the number of turns of a multi-turn magnetic circuit) is times greater than the sensitivity of a known sensor, and the accuracy of measuring the speed of movement of the moving winding of the controlled object is higher due to the reduction to a minimum of the level of the alternating component of the output signal, which is not proportional to the speed of movement, which is achieved by picking up a signal proportional to the linear speed of movement of the moving measuring winding, from the load terminals to a moving measuring winding tuned to voltage resonance.

1. Introduction

Automation of various technological processes, requiring the use of a complex of primary converters - sensors, makes it possible to quite easily carry out labor-intensive processes, save energy resources, reduce the cost of manufactured products and improve their quality by ensuring close to optimal operating modes of monitoring and control objects, both in normal and in emergency situations [1-4]. Meanwhile, one of the main obstacles to this is the lack of motion parameter sensors (DPS) (displacement, speed, acceleration, vibration, etc.) that meet modern requirements when working in extreme operating conditions with increased dust, humidity, significant temperature differences, etc. A comparative analysis of the main characteristics of existing DPDs shows that the most promising direction in solving the current problem of more efficient use of monitoring and control systems is the use of electromagnetic DPDs (EDPD), which due to their properties (high reliability and stability characteristics in extreme operating conditions, as well as a large output power) best meet the modern requirements of monitoring and control systems [3-5]. However, the existing design schemes of EDPD, in particular, linear displacement and speed sensors, are practically

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unsuitable due to the instability of sensitivity over the entire measurement range and the nonlinearity of the static characteristic [5-8]. As a result, the accuracy of monitoring and control is reduced, and in some cases, the stability margin of the system is reduced. The need for more accurate and stable measurement of technological parameters of the movement of objects of monitoring and control systems raises the problem of developing a new EDPD for simultaneous measurement of linear displacement and linear speed with improved information and technical characteristics, which explains the relevance of the research problem.

2. Methodology

We examine the well-known electromagnetic resonant motion parameter sensor (ERPM) [9], used for simultaneous measurement of linear displacement and linear speed, in order to identify its technical capabilities. The design diagram of the EDPD with the corresponding symbols is shown in Figure 1.

The sensor contains an E-shaped magnetic core 1, the base of which is two permanent magnets 2 with oppositely directed poles with magnetic fluxes summed up in the middle rod, a stationary concentrated excitation winding 3, powered from a source of alternating, in particular, sinusoidal voltage and placed on the middle rod of the magnetic core, a movable concentrated winding 4 of measurement, bridged by a capacitance 5 and the primary winding of a transformer 6 in series. Permanent magnets create a constant magnetic flux between the parallel bars of the magnetic circuit, while the excitation winding 3 provides an alternating magnetic flux between the parallel bars. If we neglect the active and reactive magnetic resistance of the magnetic circuit, then a uniform magnetic field is created in the working gap.

The magnetic flux in the middle rod is given by

$$\Phi_w = \Phi_{w.0} + \Phi_{w.m} sin(\omega t + \varphi_{exc}) \tag{1}$$

here $\Phi_{w.0} = 2F_{exc.0.} G_{\mu wf} x = F_{exc.0.} \mu_0 \frac{bx}{\delta_w}$; $\Phi_{w.m} = 2F_{exc.m.} G_{\mu wf} x = F_{exc.m.} \mu_0 \frac{bx}{\delta_w}$ ·

$sin(\omega t + \varphi_{exc})$ - constant and variable components of the worker.

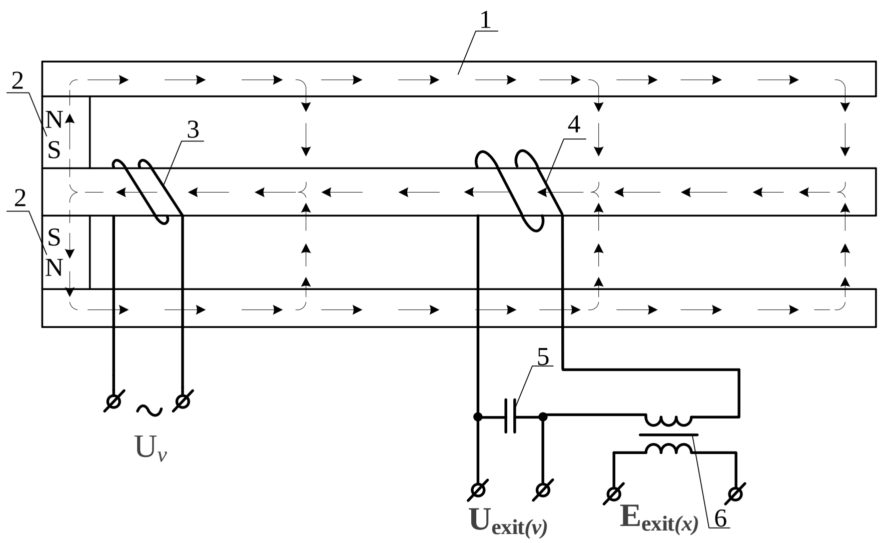

Fig. 1. Design diagram of a known motion parameters sensor

Magnetic flux in the middle long rod; $F_{exc.0.}$ magnetomotive force (MF) of a permanent magnet; $F_{exc.m.} = w_0 I_{exc.m} sin(\omega t + \varphi_{exc})$ – MDS, created by the sinusoidal current of the excitation winding; $I_{exc.m}$, ω, φ_{exc}- respectively, the amplitude value, angular frequency and initial phase of the sinusoidal current; w_0- number of turns in the field winding; $G_{\mu wf} = \mu_0 \frac{b}{\delta_w}$ - linear value of the magnetic conductivity of the working air gap between two adjacent parallel long rods, per unit length of these rods; b , X_m and δ_w - width, length of the working sections of long rods and the working air gap between two adjacent rods; μ_0- magnetic constant of a magnetic circuit or absolute magnetic permeability of air; x- coordinate of the moving measuring winding, measured from the free ends of the long rods.

When moving the movable measuring winding 4 in it, according to the law of electromagnetic induction, an electromotive force (EMF) is induced, determined by the following formula

$$e_{meas} = w_{meas} \frac{d\Phi_w}{dt} = E_v + e_x + e_{gen.} = 2w_{meas.} F_{exc.0} G_{\mu wf} v + \\ +2\omega w_0 w_{meas.} I_{exc.m} G_{\mu wf} x cos(\omega t + \varphi_{exc}) + 2w_0 w_{meas.} I_{exc.m} G_{\mu wf} v sin(\omega t + \varphi_{exc}), \quad (2)$$

here $E_v = 2w_{meas.} F_{exc.0} G_{\mu wf} v$ - the constant component of the EMF is proportional to the speed of movement of the movable winding; $e_x = 2\omega w_0 w_{meas.} I_{exc.m} G_{\mu wf} x cos(\omega t + \varphi_{exc})$ and $e_{gen.} = 2w_0 w_{meas.} I_{exc.m} G_{\mu wf} v sin(\omega t + \varphi_{exc})$- transformer (proportional to the movement of the moving winding) and generator (parasitic) components of the EMF, respectively; $v = \frac{dx}{dt}$ - linear speed of movement of the moving winding. It should be noted that the $e_{gen.}$ component is a source of dynamic error when measuring displacement.

The EMF component, proportional to the movement of the moving winding and removed from the secondary winding of transformer 6, at $v = 0$ is written in complex form as (Figure 1)

$$\dot{E}_{exit.(x)} = j2\sqrt{2}\omega w_0 w_{meas.} I_{exc} G_{\mu wf} x \quad (3)$$

The load current, according to the equivalent circuit (Figure 2), is defined as

$$\dot{I}_n = \frac{\dot{E}_{meas}}{R_{L.meas} + R_{L_1(tr)} + jX_{L.meas} + j\left(X_{L_1(tr)} - X_C\right)} \quad (4)$$

here $R_{L.meas}$, $R_{L_1(tr)}$, $X_{L.meas}$, $X_{L_1(tr)}$ - active and inductive resistance, respectively, of the moving measuring winding 4 and the primary winding of the transformer 6; X_C is the capacitance of the capacitor.

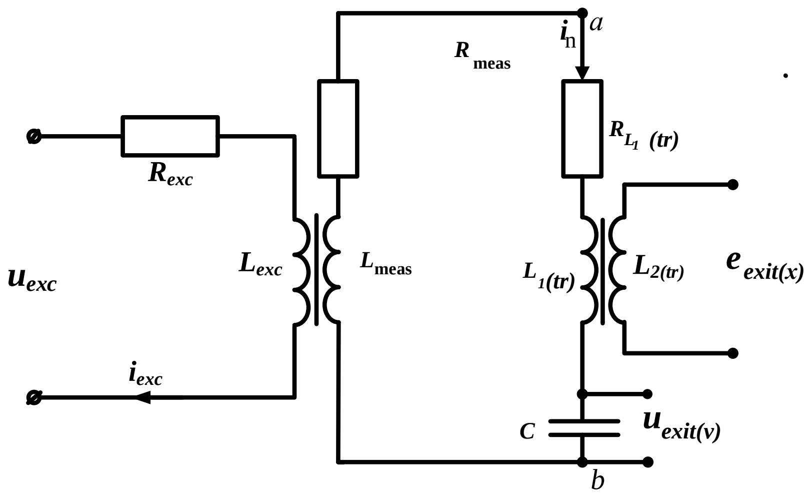

Fig. 2. Replacement diagram of the electrical circuit of a known motion parameters sensor

The output voltage, proportional to the speed of movement of the moving winding, and removed from capacitor 5 is defined as the voltage drop across the capacitance of capacitor 5, i.e.

$$\dot{U}_{exit(v)} = E_v + j\dot{I}_n X_C \tag{5}$$

The sensitivity of a known motion sensor for displacement is calculated as

$$S_{offer.(x)} = \frac{dE_{exit(x)}}{dx} \tag{6}$$

3. Result and Discussion

Now we obtain the values of output signals and sensitivity for a known motion parameters sensor with the following data: geometric dimensions of the magnetic circuit and the number of turns of the sensor windings:

$X_m = 0{,}1\ m; b = 0{,}02\ m; h = 0{,}01\ m; \delta_{\text{p}} = 0{,}01\ m; F_{exc.0} = 100$ A; $w_{meas} = 10$ turns; field winding current: $b_{tr} = 0{,}02\ m$; $h_{tr} = 0{,}02\ m$; $r_{av.} = 0{,}05$ m; $\mu = 10^4$; $\mu_0 = 4\pi \cdot 10^{-7}\ Gn/m$; $w_{tr.1} = w_{tr.2} = 500$.

In the calculations, the magnetic resistance of the steel part of the magnetic core of the sensor is neglected due to its small value compared to the magnetic resistance of the working air gap, the bulging flows at the ends of the magnetic core and in the area of the moving element of the sensor.

The linear value of the magnetic conductivity of the working gap between adjacent long rods is found as

$$G_{\mu wf} = \mu_0 \frac{b}{\delta_w} = 2{,}5 \cdot 10^{-6}\ Gn/m \tag{7}$$

Excitation MDS

$$F_{exc} = F_{exc} + I_{exc.m} w_{exc} \sin \omega t = 100 + 100 \sin 314t \tag{8}$$

Working magnetic flux

$$\Phi_w = 2F_{exc}G_{\mu wf}x = 5 \cdot 10^{-4}x + 5 \cdot 10^{-4}x \sin 314t. \quad (9)$$

The value of the EMF induced in the measuring winding when it moves along the middle long rod, determined by (2), is equal to

$$e_{meas} = w_{meas}\frac{d\Phi_w}{dt} = 5 \cdot 10^{-3}v + 1{,}57x \cos 314t + \\ +5 \cdot 10^{-3}v \sin 314t = E_v + e_x + e_{gen.}. \quad (10)$$

Now let's calculate the active and inductive resistance of the measuring winding and the primary winding of the transformer. As the wire for these windings, we select a copper conductor with a diameter $d = 0{,}4$ mm and linear resistance $R_f = 0{,}14\ Om/m$ [11].

$R_{L.meas} = R_f l_{meas} = 0{,}14 \cdot 0{,}8 = 0{,}112\ Om$ (l_{meas}- total length of the measuring winding wire at $w_{tr.1} = 500$)

$L_{meas} = 2w_{meas}^2 G_{\mu wf}x = 5 \cdot 10^{-4}x$ Gn.

$L_{1(tr)} = L_{2(tr)} = w_{tr.1}^2 G_{\mu tr.} = w_{tr.1}^2\ \mu\mu_0 \frac{b_{tr}h_{tr}}{2\pi r_{av.}} = 1{,}0$ Gn.

$X_{L.meas} = \omega L_{meas} = 0{,}157x$ Gn.

$X_{L_1(tr)} = \omega L_{1(tr)} = 314$ Om;

We will assume that the transformer is perfect [10], i.e. $M_{12} = L_{1(tr)} = L_{2(tr)} = 1{,}0\ Gn.$ – mutual inductance between the primary and secondary windings of the transformer.

We find the capacitance value of the capacitor based on the condition of maximum load current, at which the output signal, proportional to the movement of the movable winding, will be maximum. The load current at given values of e_{meas}, $R_{L.meas}$, $R_{L.tr.1}$, $X_{L.meas}$ and $X_{L_1(tr)}$ reaches its maximum value when the following voltage resonance condition is met in the measuring circuit

$$X_{L_1(tr)} = X_C \quad (11)$$

from there

$C = \frac{1}{\omega X_{L_1(tr)}} = 1{,}01424 \cdot 10^{-5}$ F.

$X_C = \frac{1}{\omega C} \approx 314$ Om.

The complex value of the alternating component of the EMF of the moving measuring winding is written as

$$\dot{E}_{meas.(\sim)} = \dot{E}_x + \dot{E}_{gen.} = j1{,}57x + 5 \cdot 10^{-3}v \quad (12)$$

If we take into account that the speed of movement of the moving part in dynamic mode ranges from 0 to 0.1 m⁄s [6,7], and the range of movement of the moving winding is from 0 to 0.1 m, then the component $\dot{E}_{gen.}$ can be omitted from expression (12) due to its small value compared to $\dot{E}_x$.

We find the following value of the current in the load using formula (4) taking into account (11) and (12)

$$\dot{I}_n = \frac{j1{,}57x}{\sqrt{2}(3{,}472 + j0{,}157x\ )} \quad (13)$$

Resistance $X_{L.meas}$ takes its maximum value at $x = X_m = 0{,}1\ m$ and is 0.0157 Om. Taking into account 3.472≫0.0157 Ohm, the load current module takes the following value

$$I_n \approx \frac{1{,}57x}{\sqrt{2}}, \text{A}. \quad (14)$$

The output signal, proportional to the movement of the moving winding, removed from the secondary winding of the transformer, according to (10), is found as

$$E_{exit(x)} = \omega M_{12} I_n = \frac{493x}{\sqrt{2}}, \text{V}. \quad (15)$$

The value of the output signal of a known sensor, proportional to the speed of movement of the movable measuring winding, removed from the terminals of the capacitor is found as

$$\dot{U}_{exit(v)} = E_v - jX_C \dot{I}_n = 5 \cdot 10^{-3}v + \frac{493x}{\sqrt{2}}. \quad (16)$$

The sensitivity of the known motion parameters sensor for displacement, calculated using formula (6), is equal to

$$S_{(x)} = \frac{dE_{exit.x}}{dx} = \frac{493}{\sqrt{2}} \quad (17)$$

At the Department of Electric Power Supply of the Tashkent State Transport University, the design of the EDPD was developed (Figure 3) [12-20].

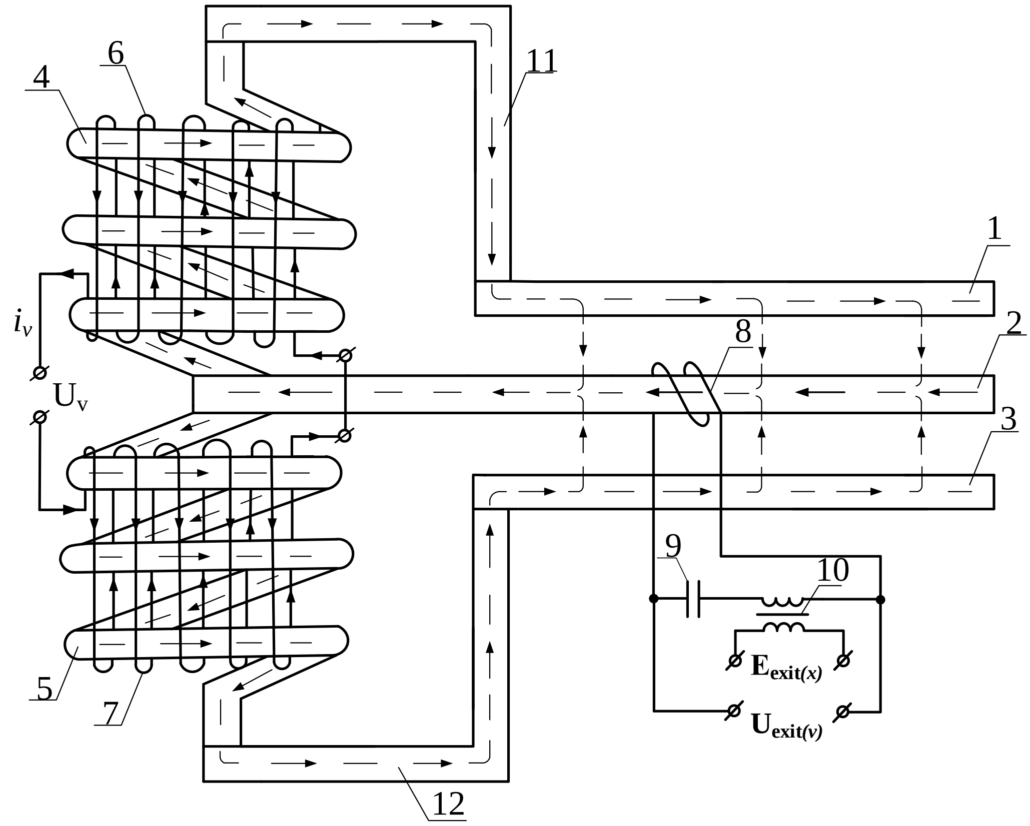

Fig. 3. Design diagram of the proposed EDPD

The motion parameters sensor contains a magnetic circuit made in the form of three long parallel rods 1,2,3, at the base of which two magnetic field sources are placed, made in the form of multi-turn magnetic circuits 4.5 with corresponding sections 6.7 of the excitation winding, interconnected like this that their magnetic fluxes are directed counter and add up in the middle rod 2, placed on the middle rod of the magnetic circuit and connected to the controlled object, a movable concentrated measuring winding 8, shunted in series with a capacitance 9 and the primary winding of the transformer 10. In this case, the capacitor and the primary winding of the transformer are tuned to resonance stress. In order to reduce the working gaps between adjacent long rods, ferromagnetic jumpers 11 and 12 are used, connecting each end part of the corresponding outermost long rod with the corresponding end of the multi-turn magnetic circuit. The excitation winding is powered from a voltage source with an output voltage in the form $u_{exc} = U_{exc.0} + U_{exc.m} sin\omega t$, where $U_{exc.0}$ is the constant component and $U_{exc.m}$, ω is the amplitude value and the angular frequency of the sinusoidal component of the excitation voltage. In this case, the parameters are selected in such a way that the inductive reactance of the primary winding of the transformer is much greater than its active resistance, i.e. $X_{L_1(tr)} \gg R_{L_1(tr)}$. Then we can assume that $R_{L_1(tr)} \approx 0$. An output signal proportional to the magnitude and direction of movement is removed from the secondary winding of the transformer, and an output signal proportional to the speed of this movement is taken from the output terminals of the measuring winding.

The motion sensor works as follows. The excitation winding is supplied with voltage $u_{exc} = U_{exc.0} + U_{exc.m} sin\omega t$ from the power source. Under the influence of this voltage, a current of magnitude $i_{exc} = I_{exc.0} + I_{exc.m} sin(\omega t + \varphi_{exc})$ appears in the excitation circuit, where φ_{exc} is the phase shift angle between the alternating components of the voltage and excitation current. This current, flowing through the turns of the field winding section, creates a magnetomotive force (MF) in each turn of the multi-turn magnetic circuit, the value of which is determined by the following formula

$$F_{exc} = F_{exc.0} + F_{exc.m} sin(\omega t + \varphi_{exc}) = w_0 I_{exc.0} + w_0 I_{exc.m} sin(\omega t + \varphi_{exc}) \quad (18)$$

$F_{exc.0} = w_0 I_{exc.0}$ and $F_{exc.m} = w_0 I_{exc.m}$ are the constant and alternating components of the MMF in each turn of the multi-turn magnetic circuit, created by the constant and alternating components of the excitation current, respectively; w_0– number of turns in one section of the field winding.

The total MMF at the ends of the multi-turn magnetic circuit of each magnetic field source is determined as the arithmetic sum of the MMF in each turn of the multi-turn magnetic circuit, i.e.

$$F_{exc\Sigma} = F_{exc.0.\Sigma} + F_{exc.m.\Sigma} sin(\omega t + \varphi_{exc}) = w_m w_0 I_{exc.0} + w_m w_0 I_{exc.m} sin(\omega t + \varphi_{exc}) \quad (19)$$

here w_m is the number of turns in a multi-turn magnetic circuit. It should be noted that in expression (19), as a first approximation, we neglect the active and reactive magnetic resistances of a multi-turn magnetic core because of their small value compared to the magnetic resistance of the working air gaps between the corresponding long rods of the magnetic core).

When moving the movable measuring winding 8 in it, according to the law of electromagnetic induction, an EMF is induced, determined by the following formula

$$e_{meas} = 2w_{meas} \frac{d\Phi_{exc}}{dt} = E_v + e_x + e_v = 2w_m w_0 w_{meas} I_{exc.0} G_{\mu wf} v + 2\omega w_m w_0 w_{meas} \cdot \quad (20)$$
$$\cdot I_{exc.m} G_{\mu wf} x cos(\omega t + \varphi_{exc}) + 2w_m w_0 w_m I_{exc.m} G_{\mu wf} v sin(\omega t + \varphi_{exc})$$

A comparative analysis of expressions (2) and (20) shows the magnitude of the emf induced in the measuring winding of the proposed electric motor when it moves with times greater than the corresponding emf of the known electric motor.

With the same above-mentioned geometric dimensions and parameters, as well as with the same assumptions, the constant component and the complex value of the alternating component of the EMF of the moving measuring winding of the proposed sensor are respectively equal

$$E_v = 2w_m w_0 w_{meas} I_{exc.0} G_{\mu wf} v = 5 \cdot 10^{-3} w_m v \quad (21)$$

$$\dot{E}_{meas.(\sim)} = j2\omega w_m w_0 I_{exc.m} G_{\mu wf} x = j1{,}57 w_m x \quad (22)$$

load current

$$I_n \approx \frac{1{,}57 w_m x}{\sqrt{2}}, \text{A} \quad (23)$$

Since the load, consisting of a series-connected capacitor 9 and the primary winding of the transformer 10 is configured for voltage resonance ($X_{L_1(tr)} = X_C$), the expression for $\dot{U}_{exit.(v)}$ takes the following form

$$\dot{U}_{exit.(v)} = E_v + \dot{I}_n R_{L_1(tr)} \quad (24)$$

With the same geometric dimensions and parameters above, as well as with the same assumptions, the useful output signals for the proposed sensor, proportional to the movement and its speed, as well as the sensitivity will be equal to

$$E_{exit(x)} = \omega M_{12} I_n = \frac{493 w_m x}{\sqrt{2}}, \text{V} \tag{25}$$

$$\dot{U}_{exit(v)} = E_v + \dot{I}_n R_{L_1(tr)} = 5 \cdot 10^{-3} w_m v + \frac{5{,}28 w_m x}{\sqrt{2}}, V \tag{26}$$

$$S_{(x)} = \frac{dE_{exit.x}}{dx} = \frac{493 w_m}{\sqrt{2}} \tag{27}$$

4. Conclusion

Thus, a comparative analysis of the obtained expressions of the output signals and the sensitivity of the known and proposed electromagnetic sensors of motion parameters showed that the sensitivity of the proposed sensor, due to the implementation of each magnetic field source in the form of a multi-turn magnetic circuit with an excitation winding section, the turns of which cover all turns of the multi-turn magnetic circuit, in w_m (where w_m is the number of turns of a multi-turn magnetic circuit) times greater than the sensitivity of a known sensor, and the accuracy of measuring the speed of movement of the moving winding of the controlled object is higher due to the reduction to a minimum of the level of the alternating component of the output signal, which is not proportional to the speed of movement, which is achieved by picking up a signal proportional to the linear speed of movement of the moving measuring winding, from the load terminals to the movable measuring winding, tuned to voltage resonance.

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