The feasibility of determining the condition of friction units of engines by the EMF magnitude

Ilmas Salakhutdinov[1*], *Denis* Molochnikov[1], *Andrei* Glushchenko[2], *Albert* Khusainov[2], and *Ilnar* Gayaziev[3]

[1]Federal State Budgetary Educational Institution of Higher Education «Ulyanovsk State Agrarian University named after P.A. Stolypin», boulevard Novy Venets, 1, 432017, Ulyanovsk, Russia
[2] Ulyanovsk State University, 42, Leo Tolstoy St., 432017, Ulyanovsk, Russia
[3]Federal State Budgetary Educational Institution of Higher Education «Kazan State Agrarian University», Karla Marksa Str., 65, 420015, Kazan, Republic of Tatarstan, Russia

Abstract. The paper is devoted to theoretical studies of the feasibility to determine the clearance size in the friction units of an internal combustion engine by the magnitude of the electromotive force (EMF) that arises in them. The effect of the contact area of the friction pairs and the clearance between them on the electrical resistance in the contact, and, accordingly, on the magnitude of the emerging EMF was theoretically confirmed. As a result of the theoretical studies, the relationship of the influence of changing clearances on the magnitude of the EMF arising in them was established. To confirm the theoretical calculations, bench studies of the UMZ-417 engine were carried out to determine the magnitude of the EMF arising in its friction pairs depending on the change in the crankshaft rotation speed, followed by micrometry of the parts. The study was carried out using the designed current collector. The obtained theoretical and experimental results confirm the feasibility of determining the condition of friction units by the magnitude of the EMF generated in them and with sufficient accuracy to determine the dynamics of the clearance size between rubbing parts.

1 Introduction

The most significant cause for the decrease in the efficiency and durability of the friction units of any mechanism is the wear of its contact surfaces. This is confirmed by numerous theoretical and operational studies of the durability of various mechanisms of transport vehicles and their individual components. It is known that these types of changes in the geometric parameters of the surfaces of rubbing components can be referred to the main three groups: mechanical wear, that is, wear from reciprocal contact of two or more surfaces under the influence of various forces and speeds of reciprocal movement; corrosion-mechanical, arising under the influence of chemically active media and materials; the third group includes the least studied process of changing the parameters of surfaces

* Corresponding author: ilmas.73@mail.ru

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

under the influence of an electric current. This type of friction, despite the lack of a unified theory of wear, at the same time can be the most informative in terms of determining the condition of friction surfaces, and, accordingly, assessing the condition of not only individual units and systems, but also the unit as a whole.

The most important unit in transport and traction machines is the source of its energy - the engine. It consists of a set of different friction units, the surfaces of which, during operation, carry out various reciprocal displacements, characterized by a wide range of load and multidirectional speed modes. It is known from the theory of solid state physics that the reciprocal interaction of rubbing surfaces is accompanied by the action on the particles of the material from which the surfaces are made, causing their oscillatory and wave motion. This results in the appearance of thermionic phenomena at the atomic level in the surface layers of the contacting material. The negative effect of electric currents on the anti-wear properties of materials is also known. Therefore, it can be assumed that, knowing the magnitude of the arising electrical quantities in the friction surfaces, it is possible to assess the condition of these friction units.

2 Materials and methods

Components and parts of friction units are machined in an appropriate way. The degree of machining a surface is characterized by its ideal smooth plane, that is, any machined surface will have surface roughness. Roughness is a certain number of protrusions and low spots on the friction surface. It is natural, when two surfaces come into contact, their interaction will be in the area of their surface irregularities. That is, the contact area will correspond to the area of irregularities located on the unit of the contacting surface. The interaction of surface irregularities will depend on the acting forces in the area of contact. It is known from the theory of friction that the normal mode is accompanied by elastic deformation of the material hills, which will occur until the moment of equal action of the total pressing force and the total reaction force of the material to this action [1 - 5]:

$$N = \sum_{i=1}^{n_i} N_i, \tag{1}$$

where n_i – the number of protrusions coming into contact, pcs.; N_i – the force of reaction of the protrusion material to the deforming force in contact, MPa.

In this case the area of the contact surface in the friction pair is

$$S = \left(\frac{2,2\Pi_r^{2/3}}{E \cdot h_m^{1/3}} \right) \cdot N^{6/7} \cdot n_o^{1/7}, \tag{2}$$

where Π_r – the number of protrusions in contact, pcs.; E – Young’s modulus, Pa; h_m – the greatest height of contacting protrusions, mm; n_o – the number of protrusions on a real contacting surface, pcs.

When the reciprocal displacement of the friction surfaces takes place, relative to both rotational and reciprocating motion, depending on the purpose of the friction unit, an electric current will arise in the contact. It is known that the current path is not linear, it is curved, which depends on the properties of the material and the load distribution in the contact. This leads to the fact that the current path is "pulled together" in some areas of the contact material and "stretched" (scattered) in others. Then the resistance of one or the other contact surfaces can be expressed as

$$R = \rho \cdot l \cdot \tfrac{1}{A}, \tag{3}$$

where l – length dynamics of a contact pair, mm; ρ – specific resistance of the material, Ohm·mm.

In accordance with Formula (3), one can say that the resistance of the material surfaces in the contact area will not be the same. In particular, in the "contraction" area, it will be determined by the following expression

$$R = \frac{0,45 \cdot \rho \cdot E^{5/7} \cdot h^{4/7}}{r^{1/7} \cdot N^{5/7} n_o^{1/4}}. \tag{4}$$

where r – the mean value of the protrusion radius of a contact surface, mm.

The power plant of a vehicle can be considered as a typological system due to the fact that its elements perform different multidirectional movements of some surfaces in contact with respect to others, and also that these contacts are separated by a lubricating medium to prevent convergence and reduce wear. In this case, any of the motor contacts is a three-element system I metal - III lubricant - II metal. Since the lubricant will always contain substances of different chemical activity, particles of dissolved water and particles of friction products, it will have the properties of an electrolyte. Assuming that, this system can be considered an electrochemical system, in this case the basic laws of electrochemistry can be applied to it (Fig. 1).

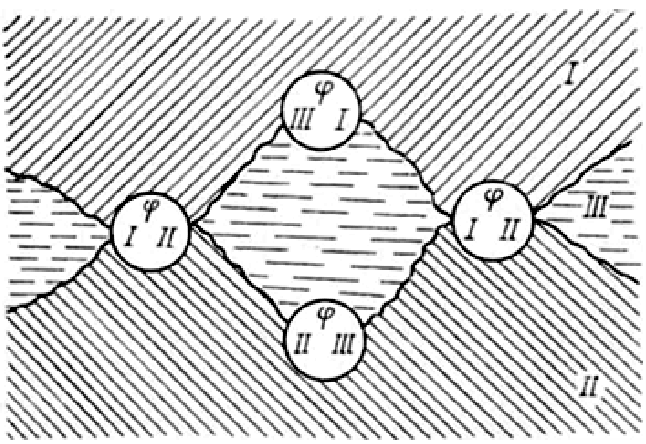

Fig. 1. Diagram of the electrochemical system of the friction unit: I - metal (material) of the first rubbing surface; II - metal (material) of the second rubbing surface; III - lubricant (electrolyte).

If to accept this theory, then the operation of the friction unit can be described as follows. Since the process of interaction of two surfaces is accompanied by deformation of individual protrusions on one or the other friction surface during their relative displacement relative to each other, then in the presence of a lubricant with certain electrolyte properties, microgalvanic pairs will be formed at the moment of contact of protrusions [6-8].

In this case, at the moment of separation of the protrusions and the destruction of the galvanic micro-pair between the metals, a contact potential difference will appear (${}_{I}\varphi_{II}$), and at the boundary of the lubricant in contact with one or the other friction surface, a potential difference will arise ${}_{III}\varphi_{I}$ and ${}_{II}\varphi_{III}$.

That isan electromotive force (EMF) will be formed, at the moment of contact breaking. And it, in turn, will contribute to the occurrence of a redox reaction in the contact, the result of which is increased wear of the contact surfaces.

Since the potential difference is the result of the energy spent to ensure the exit of the charge carrier from the material of the friction surface or lubricant, for the considered electrochemical scheme, its value will be expressed as

$$\varphi = W_I - W_{III} - W_{II}, \tag{5}$$

where W_I – energy of the charge carrier exit from material surface *I*; W_{II} – energy of the charge carrier exit from the surface of friction material *II*; W_{III} – energy of the charge carrier exit from lubricant *III*.

Taking into account that the temperature in the friction unit is not a constant value, then

$$\varphi = \frac{KT}{e} \ln \frac{n_2}{n_1}, \tag{6}$$

where K – Boltzmann constant, J/K; T – temperature in a friction unit, K; e – the charge of an electron, C; n_1 and n_2 - the concentration of electrons in the materials of the friction surfaces respectively.

Making the assumption that the temperature of the lubricant will have the temperature of one of the friction surfaces in the unit, we will obtain

$$\varphi = \varepsilon = \frac{K}{e}\left(T_I - T_{II}\right) \ln \frac{n_2}{n_1}. \tag{7}$$

Then we obtain that ε represents thermoelectromotive force.

Thus, considering Expression (7), it can be stated that the magnitude of the electric current arising in the friction unit will be determined by the characteristics of the rubbing surfaces and the temperature in contact.

Considering the above expressions, the friction unit operation process can be represented as follows. The initial period of the operation of parts in contact is accompanied by a decrease in energy on the surface of the friction material, which facilitates the escape of electrons (charge carriers). This leads to an increase in the potential difference in the system under consideration and the activation of electrochemical processes, and the presence of a chemically active lubricant, during the operation of the tribo unit, leads to the formation of oxidizing films on the friction surfaces. This is accompanied by an adsorptive decrease in the surface strength of the material in contact, and, as a consequence, an increase in its wear.

Thus, the change in the basic strength properties of the materials of the friction surfaces is primarily associated with the occurrence of EMF and electric current in the working contact [10-14].

Proceeding from this, the considered electrochemical system can be represented as a capacitor with a field strength (*E)*, the charge of one of the friction surfaces can be expressed through the distance between the capacitor plates, that is, through the distance between the contact surfaces of the friction unit

$$q = \varepsilon_o \frac{S}{s} \varepsilon, \tag{8}$$

where S – the area of the contact surface, mm^2; ε_o – dielectric permeability of the medium in a clearance.

In this case, the relationship between the magnitude of EMF and clearance width in rubbing surfaces will be presented in the form

$$\varepsilon = \frac{\varepsilon_o Sq}{s} = \frac{\varepsilon_o \left(\dfrac{2,2\Pi_r^{2/3}}{E \cdot h_m^{1/3}} \right) \cdot N^{6/7} \cdot n_o^{1/7} q \cdot}{s}. \tag{9}$$

Analysis of the obtained expression shows that the magnitude of the arising EMF will decrease when the distance between the friction surfaces increases. This analytical relationship makes it possible to make an assumption about the possibility of determining the size of the clearance in the engine friction units by the magnitude of the EMF arising in this unit and to use this method to carry out diagnostic assessment of friction units and rubbing parts in them.

3 Results and their discussion

To confirm the obtained analytical relationships, the change in the magnitude of the EMF was theoretically determined depending on the change in the clearance size between the surfaces of the friction unit (Fig. 2). In the calculations, the standard values of clearances in the friction units of an engine of the Ulyanovsk Motor Plant UMZ-417 were used.

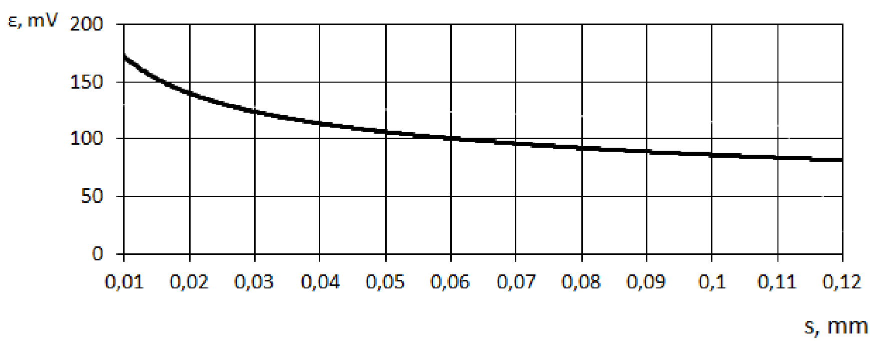

Fig. 2. Relationship between EMF (*ε*) and the clearance width (*s*) in rubbing parts of a friction unit.

As we can see, graphically, the change in the EMF magnitude in view of the clearance in the contact surfaces of the friction unit is described by a power function in the form

$$\varepsilon = 172,58 s^{-0,3009}. \tag{10}$$

There is an assumption that the EMF magnitude under operating conditions of an engine may differ from the obtained theoretical values due to many factors that could not be taken into account in theoretical studies. To establish the relationship between the EMF magnitude and the condition of the units in a real engine, bench studies were carried out. An engine of the same manufacturer and the same brand UMZ-417 was used for the study.

The EMF was determined using a developed measuring complex and a specially designed current collecting device (Fig. 3, 4) installed on the output end of the engine crankshaft. A contact made of liquid metal was used to receive and transmit electrical signals from the rotating surface of the crankshaft to the measuring device (Fig. 3).

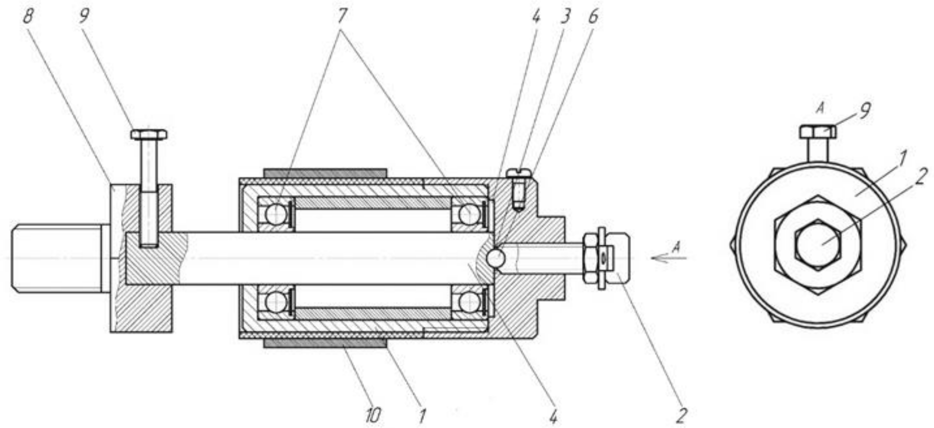

Fig. 3. Diagram of the current collector.

The current collector represents a housing 1, with a fixed contact 2 located inside the housing, the interaction of a fixed contact 2 with a movable contact 4 is carried out through a layer of liquid metal 3. The liquid metal is placed inside an annular cavity 5, which is between contacts 2 and 4. There is also a ball made of steel St3 between these contacts on the longitudinal axis of symmetry of the current collector housing. All the time this ball is in a layer of liquid metal 3. The axis of the current collector is mounted on bearings 7 pressed in the holder of the movable contact 4. The transient contact 8 is designed to connect the engine crankshaft with the axis of the current collector. The transient contact on the shaft is fixed with a screw 9.

To prevent the current collector from rotating and damping the resulting vibrations, a clamp 11 is installed on the housing 1 with a rubber gasket 2 ... 4 mm thick [14-16].

Manipulation with the current collector (Fig. 3, 4) is carried out in the following order.

The adapter 1 of the current collector is installed on the crankshaft of the engine and is fixed with the screw 9. Contact 2 is connected to the measuring complex. After checking the electrical circuit, the engine is started. When the engine is running in pairs of fit the "cylinder liner - piston ring - piston - elements of the crank mechanism - engine crankshaft", an electromotive force arises. The electrical magnitude of the EMF signal in the form of a pulse from the crankshaft is transmitted through the movable contact 2, a layer of liquid metal, a steel ball and fixed contact 3 to a millivoltmeter (not shown in Fig. 3 and 4).

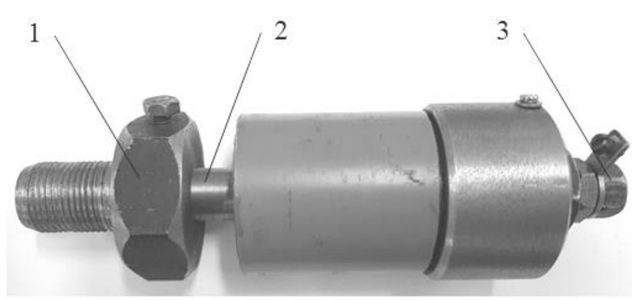

Fig. 4. Designed current collector.

According to the research results, using the rule of summation of the EMF values in electrical circuits during their processing, the EMF values were obtained for individual friction units of the tested engine (Table 1). For the reliability of the data obtained, two types of measuring instruments Fluke and V1net were used. The studies were carried out in two modes of engine operation at crankshaft rotation speeds of 800 and 1500 min^{-1}. In the course of the study, the standard values of engine indicators were maintained: fuel consumption, coolant temperature in the cooling system, crankcase oil temperature in the engine lubrication system, air temperature in the test bench premises, exhaust gas temperature, engine load. Before starting the measurements, we calibrated the Fluke and V1net measuring devices, as well as the specially designed current collector used.

Table 1. EMF values in the friction units of an engine.

Device	Crankshaft rpm. min^{-1}	Link measured			Total value of EMF, mV ≈
		Piston – cylinder liner	Engine block - cylinder liner	Engine block - crankshaft	
		EMF magnitude, mV ≈			
Fluke	800	87	67	238	392
	1500	20	12	193	225
V1net	800	37	90	200	327
	1500	25	13	191	229

For convenience of processing the obtained data of engine bench tests, their interpretation is presented in a graphic form (Fig. 5). When analyzing the results of measuring the EMF in bench conditions of the UMZ-417 engine using two measuring instruments and at two different speeds of the crankshaft, the following was established.

At the operating mode corresponding to the engine crankshaft speed of 800 min^{-1}, the total value of the EMF magnitude in the link measured of the cylinder liner - engine block - crankshaft - current collector (CC) was 327 - 392 mV. At the same time, the EMF in the friction pair piston - cylinder liner was 37 - 87 mV, in the friction pair liner - engine block - 67 - 90 mV, in the friction pairs of the crank mechanism - 200-238 mV (Fig. 5).

At the operating mode corresponding to the engine crankshaft speed of 1500 rpm^{-1}, the total value of the EMF in the links liner - engine block - crankshaft - current collector (TSC) was 225 - 229 mV. In this case, the EMF in the friction pair piston - cylinder liner was 20 - 25 mV, in the friction pair liner - engine block - 12 - 13 mV, in the friction pairs of the crank mechanism - 191 - 193 mV (Fig. 5).

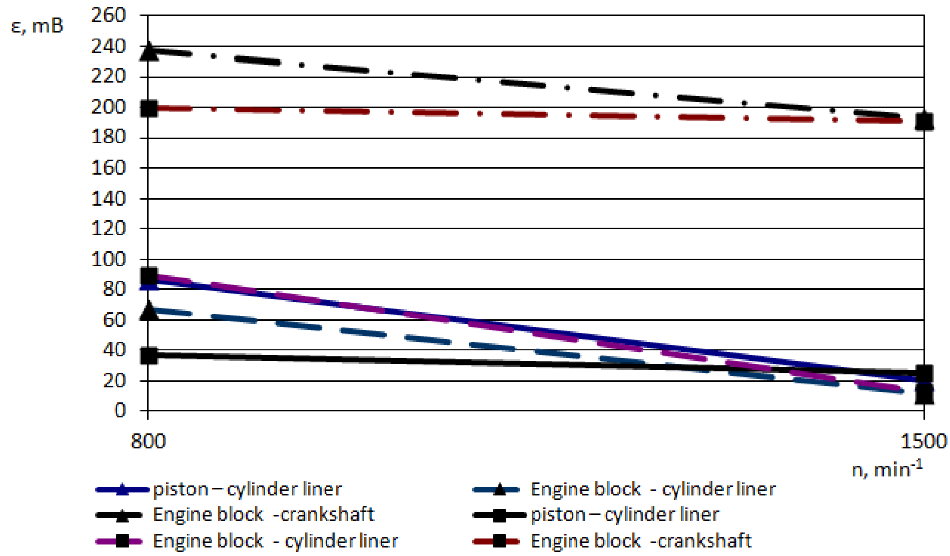

Fig. 5. Relationship between EMF (*ε*) and clearance size (*s*) in a friction unit.

To establish the relationship between the obtained EMF values and the clearance in the measured friction pairs, the engine was disassembled after bench tests. After disassembly the clearances in the friction units were measured using the method of micrometry.

Based on the measurements, it was found that conformance of the results of the theoretical calculation and bench studies with the theoretical and study values of the EMF was: for the friction unit, the cylinder liner - piston - 1%, for the friction units of the crank mechanism (connecting rod journal - connecting rod, main journals - engine block) - 15.1%. In the latter case, a large span of the discrepancy between the values is explained by the fact that during the study, the total value of the EMF was measured, and the clearance measurement was carried out for individual rubbing pairs.

4 Conclusion

The obtained analytical relationships, the results of theoretical calculations and the results of bench studies of the engine prove that the proposed method for determining the condition of the engine by the EMF magnitude arising in its friction units can be used for technical diagnostic assessment not only of engines, but also of other machine units.

References

1. A. A. Zamaidinov, A. K. Subaeva, M. I Subaev, I. R Salakhutdinov, Astra Salvensis, **5(10 S1)**, 505-511 (2017)
2. A. K. Subaeva, A. A. Zamaidinov, M. I. Subaev, I. R. Salakhutdinov, J. Fundam. Appl. Sci., **9 (1S)**, 1964-1973 (2017)
3. A. K. Subaeva, A. A. Zamaidinov, M. I. Subaev, I. R. Salakhutdinov, J. Fundam. Appl. Sci., **9 (1S)**, 1956-1963 (2017)
4. D. A. Ukhanov, A. P. Ukhanov, V. A. Perov, Vestnik of Ulyanovsk State Agricultural Academy, **1 (41)**, 21-25 (2018), doi:8286/1816-4501-2018-1-21-25.

5. A. Khokhlov, A. Khokhlov, D. Marin, D. Molochnikov, I. Gayaziev, In Proceedings of International Scientific-Practical Conference "Agriculture and Food Security: Technology, Innovation, Markets, Human Resources" (FIES 2019), 00077 (2020), doi: 10.1051/bioconf/20201700077.
6. A. Glushchenko, D. Molochnikov, A. Khokhlov, E. Proshkin, I. Gayaziev, In Proceedings of International Scientific-Practical Conference "Agriculture and Food Security: Technology, Innovation, Markets, Human Resources" (FIES 2019), 00018 (2020), doi: 10.1051/bioconf/20201700018.
7. A. Glushchenko, A. Khokhlov, D. Molochnikov, A. Husainov, E. Proshkin, I. Gayaziev, IOP Conf. Ser.: Earth Environ. Sci., **403(1)**, 012099 (2019), doi: 10.1088/1755-1315/403/1/012098.
8. A. Glushchenko, A. Khokhlov, D. Molochnikov, I. Salakhutdinov, E. Proshkin, I. Gayaziev, IOP Conf. Ser.: Earth Environ. Sci., **403(1)**, 012098 (2019), doi: 10.1088/1755-1315/403/1/012098.
9. A. V. Morozov, G. D. Fedotov, N. I. Shamukov, Vestnik of Ulyanovsk State Agricultural Academy, **4(44)**, 39-44 (2018), doi:10.18286/1816-4501-2018-4-39-44
10. D. M. Maryin, I. R. Salakhutdinov, D. E. Molochnikov, R. N. Musyakimov, I. I. Gayaziev, Vestnik of Kazan State Agrarian University, **14**, **№ 4-2(56)**, 64-68 (2019)
11. A. A. Glushchenko, D. E. Molochnikov, S. A. Yakovlev, I. N. Gayaziev, Vestnik of Kazan State Agrarian University, **3(50)**, 81-84 (2018)
12. D. Molochnikov, R. Khalimov, I. Gayaziev, D. Rudoy, A. Olshevskaya, E3S Web Conf., 08006 (2020), doi: 10.1088/1755-1315/403/1/012014.
13. A. V. Morozov, G. D. Fedotov, D. R. Musharapov, Vestnik of Ulyanovsk State Agricultural Academy, **2(46)**, 19-23 (2019), doi:10.18286/1816-4501-2019-2-19-23.
14. V. I. Dolgov, V. I. Kurdyumov, A. A. Pavlushin, Vestnik of Ulyanovsk State Agricultural Academy, **1(41)**, 6 – 10 (2018), doi:10.18286/1816-4501-2018-1-6-10.
15. V. I. Kurdyumov, E. S. Zykin, V. E. Gavrilova, Vestnik of Ulyanovsk State Agricultural Academy, **2 (42)**, 13 – 17 (2018), doi:10.18286/1816-4501-2018-2-13-17.
16. Yu. M. Isaev, N. M. Semashkin, S. A. Kalenkov, Vestnik of Ulyanovsk State Agricultural Academy, **3 (43)**, 6 - 11 (2018), doi:10.18286/1816-4501-2018-3-6-11.