Experimental Study of the Efficiency of the Differential Pump of Electromagnetic Action on the Basis of Mathematical Modeling of the Parameters of Its Operation

Bogdan Korobko, Anton Kivshyk, and Dmytro Kulagin

Abstract The operation of a differential pump of electromagnetic action operating on the principle of an inductive electromagnetic accelerator is considered. To improve the accuracy of engineering calculations and analysis of the pump, its mathematical model was developed using Newton's and Hooke's laws, the method of dimensional analysis, the Reynolds and Froud criteria. The analysis of the mathematical model of the pump operation was carried out and the design parameters that most influence the efficiency of its operation were determined. The problem of improving the operation of the differential pump by increasing the speed of its valves is solved. The dynamics of the relative motion of the discharge valve of the plunger of the differential pump is analyzed, using the mathematical model of its operation. A parametric expression is obtained that determines the operation time of the differential pump valve. On this basis, directions for improving the operation of the pump were found and tested experimentally on a prototype. The dependence is obtained, which allows to draw conclusions about which parameters directly affect the value of the valve operation time: spring stiffness, plunger size, location of the ball relative to the coil winding, friction forces of the sleeve seals, energy loss in valve assemblies. It is established that uniform pumping of the material is achieved by reducing the time to open and close the discharge valve, which is achieved by reducing the weight of the shut-off element. The operation of pump valves with shut-off elements made of different materials has been investigated experimentally. The value of the parameter of the mass of the shut-off element at which the optimal mode of operation of the pump is achieved. By setting the minimum operating time of the pump valve, its performance is improved.

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One of the problems in finishing work in construction is the creation of effective designs of pumps for pumping finishing materials. This problem is solved by the use of electromagnetic pumps operating on the principle of inductive electromagnetic accelerator. The undeniable advantage of this design is its relative simplicity and minimal number of moving parts.

However, minimizing the operating time of the working body of the pump will significantly improve its performance and expand its scope.

The problem with improving the design of modern pumps is the relatively low accuracy of engineering methods of their calculation, including calculations of their characteristics in nominal conditions.

The analysis of mathematical model of work of the pump will allow to reveal the most significant parameters variation of which will enable reaching the minimum time of operation of a working body of the pump.

1 Review of the Latest Research Sources and Publications

Electromagnetic pumps for pumping finishing materials are alternate current hydrodynamic machines. The moving part in them is the working body and the mixture that is pumped due to the action on the plunger of the magnetic field created by the alternate current winding [1, 2].

After analyzing the existing models of pumps, it was found that the differential pump of electromagnetic action is not sensitive to external factors, has the highest efficiency among analogues due to the small number of parts that are subject to active wear. The design of the differential pump provides its mobility and convenience in operation. In works [3–8] the analysis of the existing constructive schemes of the equipment, the basic means of small mechanization of manual work in construction, types of working bodies of mortar pumps is carried out, authors [10–16] offered a new design of the small differential pump of electromagnetic action.

The authors of [9] obtained mathematical models in the form of differential equations that reflect the variation in time of the speed of the plunger of the differential pump for finishing materials in the full cycle, presented a graphical interpretation of changes in the speed of the plunger over time. Also in [9] by analyzing the mathematical model, some geometrical parameters of the pump were improved, such as the size of the spring to ensure the preservation of mechanical energy during operation.

2 Problem Statement

Therefore, the purpose of this study is to further improve the design of the differential pump of electromagnetic action based on the analysis of the parameters included in the mathematical model of its work, obtained by the authors in [9]. For this purpose it is necessary: to analyze dynamics of relative movement of the discharge valve of the plunger of the differential pump, using mathematical model of its work. Obtain a parametric expression that determines the operating time of the differential pump valve. On this basis, find ways to improve the operation of the pump and test them experimentally on a prototype.

3 Basic Material and Results

In this research it's investigated the design of the differential pump for injection of finishing material, the structure of which is shown in Fig. 1.

The working element of the pump is a steel plunger, which moves in translational motion. When an electric current is applied to the drive of the differential pump, the force of the magnetic induction moves the plunger to the left.

When the working body moves at different intervals, the discharge and suction valves work alternately (Fig. 2).

Therefore, the drive of the pump 3 is supplied with an electric voltage, which has an alternating nature and forms a magnetic field, the force of which is directed at the plunger, moving it to the left. The plunger begins to retract into the coil, closing the suction valve and opening the discharge. The working chamber of the pump is filled with finishing material. During the transportation process, the pressure in the magnifying fitting begins to rise. The increase in the speed of the working body is due

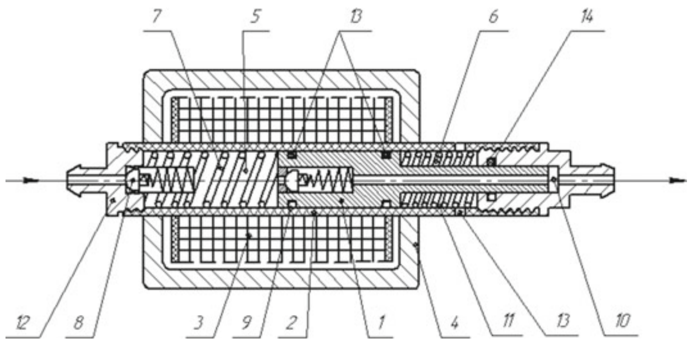

Fig. 1 Differential pump of electromagnetic action: 1—plunger; 2—frame; 3—coil; 4—magnetic coil; 5—suction cavity; 6—compensation spring; 7—working spring; 8—suction valve; 9—discharge valve; 10—compensation chamber; 11, 12—injection and suction fittings; 13, 14—cuff seals

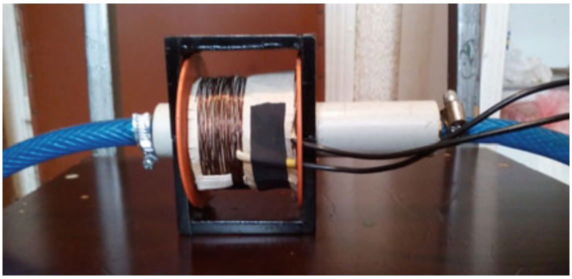

Fig. 2 The main design of the pump

to the increased pressure of the whitewashing material. In the first cycle of pumping begins to compress the working spring 7 and lengthen the compensation spring 6.

As the coil current decreases, the magnetic induction decreases and, at the same time, the speed of the plunger decreases—until the cessation of movement. However, the stop of the working body is carried out a little earlier than the complete reduction of magnetic induction—when the moment of balance of magnetic induction and compression force of the working spring 7. When the sinusoid changes direction, the diode in the power supply removes its lower part and during the movement of working body to the right the magnetic field doesn't act upon the plunger.

The length of the working spring increases by pushing the plunger to the right. The speed of the working body begins to increase. When passing the plunger in the extreme right position, the discharge valve 9 is closed and the pumping cycle is repeated. The increase in transport pressure is proportional to the increase in travel speed.

At the same time, the absorption valve 8 opens and the finishing material is poured into the working volume of the pump. When changing the position of the plunger to the right, the resistance of the working spring 7 decreased. The increase in the length of the spring is limited by the force from the whitewashing material, the force of retraction of the finishing material into the working chamber and the resistance of the compensating spring. As the force of ejection of the spring 7 decreases, the speed of the working body decreases, while the performance of the pump decreases.

By the time the plunger stops, current is supplied to the solenoid and the transport process is repeated.

Thus, the process of pumping the mixture by the pump consists of two cycles, each of which is primarily determined and depends on: the nature of the corresponding movement of the working plunger and those moments t_i when the discharge and suction valves are opened and closed.

Among other factors for improving and harmonizing the operation of the pump is related to the knowledge of which parameters depend on these time points t_i. To establish one of these dependences, we examine the dynamic state of the discharge valve 9 of the plunger 1, considering this valve as a material point whose mass is equal to the mass m_9 of this valve, and entering into consideration the coordinate system OXY and $O_1X_1Y_1$. The beginning of the reference of the Oxy system is connected

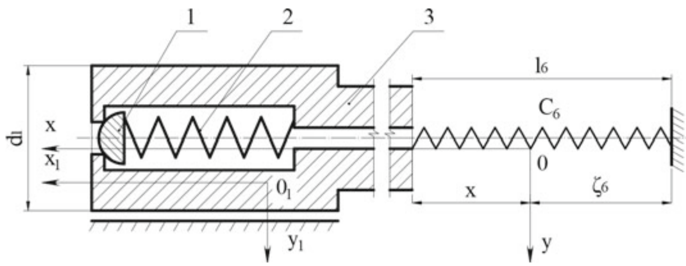

Fig. 3 Kinematic scheme of the differential pump valve due to the influence of bodies on each other, taking into account the force of inertia

with the Earth, which determines its inertia, and the beginning of the reference of the system O1x1y1 is connected with the plunger 1 (Fig. 3).

Since in [9] it was found that this plunger moves translationally, but unevenly, according to [10] the coordinate system O1x1y1 is non-inertial.

The motion of bodies in inertial reference frames can be described by the same equations of motion as in inertial ones, if, along with the forces caused by the influence of bodies on each other, the forces of inertia are taken into account.

Consider the dynamics of the relative motion of the discharge valve of the plunger during the first cycle of pumping. The basic equation of the dynamics of the absolute movement of the discharge valve is as follows.

$$m_9 * \vec{a}_9 = \sum_{i=1}^{\lambda} \vec{F}_i \tag{1}$$

where $\vec{a}_9$—absolute acceleration of the valve; $\sum_{i=1}^{\lambda} \vec{F}_i$—geometric sum of forces acting on the valve; λ—the number of these forces.

Since in this case the portable movement for the valve is the translational movement of the plunger, the absolute acceleration is equal to the geometric sum of two accelerations: relative and portable, in which case due to the translational type of portable movement Coriolis acceleration of the valve is absent.

Given the above, the law of absolute movement of the valve takes the form.

$$m * \vec{a}_9^r + m * \vec{a}_9^e = \sum_{i=1}^{\lambda} \vec{F}_i \tag{2}$$

Determining the product of the mass of the valve on its relative acceleration, we obtain the basic equation of the dynamics of the relative movement of the valve in the form:

$$m_9 * \vec{a}_9^r = \sum_{i=1}^{\lambda} \vec{F}_i + \vec{\Phi}_9^e \tag{3}$$

The last equation shows that the relative movement of the valve can be considered as absolute if to the forces acting on this valve to add its transfer force of inertia. That is, in the inertial reference system OXY the movement of the valve is only the result of forces acting on it (or the result of its mechanical interaction with other material bodies), and in the non-inertial system $O_1X_1Y_1$ the movement of the valve is both the result of forces acting on it and the result of the $O_1X_1Y_1$ If the action of forces is a dynamic factor in the acceleration of the valve, then the movement of the reference system is a kinematic factor in the establishment of this acceleration.

If we replace the portable movement of the valve with the movement of the plunger, replace the acceleration of the plunger according to Newton's second law and project the vector equality on the horizontal axis, we obtain an expression to determine the projection of the acceleration of the plunger on the axis Ox.

$$\begin{gathered}\frac{d_X^2}{dt^2} = \frac{dv}{dt} = \frac{Q_0}{m} * \sin\frac{\pi t}{\tau} - \frac{(c_6 + c_7)}{m} * x + \\ + \frac{c_6(l_{6ned.} - \varsigma_6)}{m} - k\frac{\sqrt{\pi(1-\gamma^2)}}{2*m}\mu d_1 v,\end{gathered} \tag{4}$$

where v—the speed of the working plunger; x—is the coordinate that determines the position of the plunger in the inertial coordinate system OXY; m—mass of the plunger; Q_0—the maximum value of the modulus of the driving (turbulent) force generated by the magnetic induction of the coil of the differential pump acting on the plunger; τ—the time of movement of the plunger to the left from its initial position to the final; c_6—is the stiffness coefficient of the compensation spring; c_7—is the stiffness coefficient of the working spring; l_{6ned}—the length of the undeformed compensation spring; ς_6—the length of the spring in the extreme right position of the plunger; k—is the dimensionless coefficient; γ—"diameter reduction factor"; μ—coefficient of dynamic viscosity of the finishing material pumped by the pump; d_1—is the inner diameter of the body (cylinder) of the working plunger (or the outer diameter of the plunger, or the diameter of the suction working cavity (chamber).

Having the equation of relative motion of the discharge valve, rejecting the balanced systems of forces, consider the forces acting directly on it:

– the force of elasticity of the spring;
– force of injection pressure, which is a measure of mechanical action on the valve of the part of the finishing material that is being processed by the pump, which is already in the discharge cavity (chamber) and outside the pump in the network (in the pipeline);
– the force of excess pressure, which is a measure of the mechanical action on the valve of the part of the finishing material, which is filled with the suction working cavity (Fig. 4).

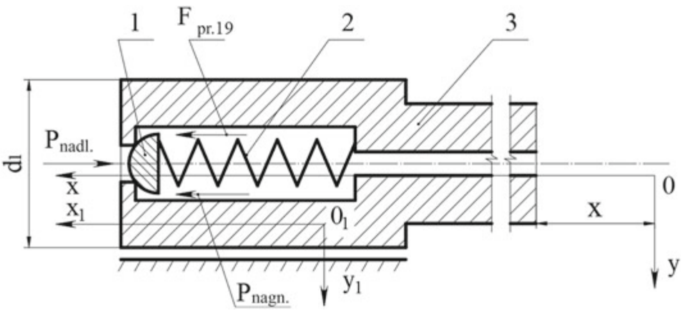

Fig. 4 Kinematic scheme of the pump valve

Let's find out the meaning of these forces. According to Hooke's law, the modulus of elastic force is equal to the product of the stiffness coefficient for spring deformation. The force of injection pressure depends on the specific location in the space of the injection network (pipeline); we assume in this study that in the conditions of each of the possible cases the modulus of this force is a constant.

Excess force is not constant and is quite difficult to depend on several technological and design parameters, but the most influential on the value of the modulus of this force is the value of reducing the volume of the suction working cavity (chamber).

We take into account that the discharge valve carries out its relative movement only along the axis O1 × 1 due to which the vectors of its relative acceleration and relative velocity are projected on this axis only in real (natural) quantities. Substituting all the values and values set in one way or another in the acceleration equation, we obtain the equation of change in the amount of relative movement of the valve:

$$\begin{aligned} d(m_9 * v^r_{9x1}) = {} & (c_{19} * \xi_{19} + P_{nagn,} - \frac{\pi * d_1^2}{4} * k_5 * f(x) - \frac{m_9 * Q_0}{m} * \sin\frac{\pi t}{\tau} \\ & - \frac{m_9 * (c_6 + c_7)}{m} * x + \frac{m_9 * c_6 (l_{6ned,} - \varsigma_6)}{m} - k\frac{m_9 * \sqrt{\pi(1-\gamma^2)}}{2 * m}\mu d_1 * v) * dt, \end{aligned} \tag{5}$$

As for emergence and growth of speed of movement of the valve it is necessary to fulfill conditions of growth of quantity of movement that mathematical condition of movement of the valve (after integration of both parts within size of time of opening of the injection valve)

$$\begin{aligned} & (c_{19}\xi_{19} + P_{nagn} + \frac{m_9 c_6 (l_{6ned,} - \varsigma_6)}{m}) * t_1 + \frac{m_9 Q_0 \tau}{\pi m} * (\cos(\frac{\pi t_1}{\tau}) - 1) \\ & > \frac{\pi d_1^2}{4} * \int_0^{t_1} k_5 * f(x) * dt + \frac{m_9 (c_6 + c_7)}{m} * \int_0^{t_1} x * dt + k\frac{m_9\sqrt{\pi(1-\gamma^2)}}{2 * m}\mu d_1 * \int_0^{t_1} v * dt. \end{aligned} \tag{6}$$

The obtained dependence allows us to draw conclusions about which parameters directly affect the value of the valve operation time. It is impossible to obtain its analytical solution due to incoherent integrals in the right part, however, the influence of parameters is obvious, including: spring stiffness, plunger size, location of the ball relative to the coil winding, friction seals, energy loss in valve assemblies.

The greatest influence on energy losses in the valve units of the pump is the ratio of the diameters of the ball and the socket (which is 4/3), the height of the ball above the plane of the socket, the mobility of the mixture and the mass of the locking element.

Thus, it is established that uniform pumping of the material is achieved by reducing the time to open and close the discharge valve, which is respectively achieved by reducing the weight of the shut-off element (Fig. 5).

To study the effect of the mass of the shut-off element on the speed of the valve, an experiment was conducted during which the operation of the pump with shut-off elements made of different materials was investigated.

To determine the speed of operation of the valve with a shut-off element from the above materials, it was first determined the mass of each of them (Table 1):

Acceleration and operating time were determined experimentally, the influence of resistance and density of the pumped medium was neglected because its area of interaction with the shut-off element is insignificant. The authors also suggested that the speed of the shut-off element and the plunger are equal, based on the fact that the discharge valve is mounted in the plunger.

Fig. 5 Locking elements from different material (from left to right): plastic, steel, rubber, cold welding, epoxy glue

Table 1 Masses of locking elements

#	Locking element material	The average value of the mass from a series of 6 measurements, g
1	Polyvinyl chloride (plastic)	0,221
2	Glue on the basis of epoxy resins of cold hardening (epoxy glue)	0,304
3	Rubber amortization, special (rubber)	0,432
4	Crystallized metal welded bath (cold welding)	0,431
5	Low-carbon steel with a density of 7.86 g/cm^3	0,862

Table 2 Dependence of mass and acceleration of the locking element on the material from which it is made

#	Locking element material	Acceleration of the locking element m/s^2
1	Polyvinyl chloride (plastic)	0,04
2	Glue on the basis of epoxy resins of cold hardening (epoxy glue)	0,03
3	Rubber amortization, special (rubber)	0,02
4	Crystallized metal welded bath (cold welding)	0,02
5	Low-carbon steel with a density of 7.86 g/cm^3	0,01

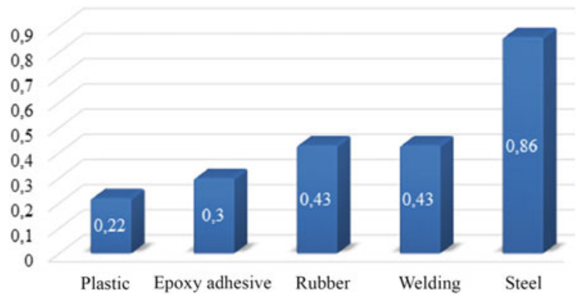

Fig. 6 Diagram of the dependence of the operating time of the discharge valve on the material of the shut-off element

The operating time of the discharge valve was determined by Newton's second law and the dependences of classical dynamics. The obtained data are shown in Table 2.

As you can see from the table, the locking element has the greatest acceleration, made of plastic. Using the described technique, it was determined that for the locking element made of plastic, the valve speed will be 8.63 m/s.

The dependence of the operating time of the discharge valve on the material from which the shut-off element is made, is shown in Fig. 6.

4 Conclusions

To increase the accuracy of engineering calculations and analysis of the pump, its mathematical model was developed.

The analysis of the mathematical model of the pump operation is carried out. The dynamics of the relative movement of the discharge valve of the plunger of the differential pump is analyzed taking into account the forces of inertia. A parametric expression is obtained that determines the operation time of the differential pump valve. The design parameters that determine the effectiveness of its work were determined. These include: spring stiffness, plunger size, location of the ball relative to the coil winding, friction forces of the seals, energy loss in the valve assemblies. The greatest influence on energy losses in the valve units of the pump is the ratio of the diameters of the ball and the socket (which is 4/3), the height of the ball above the plane of the socket and the mobility of the mixture.

The operation of pump valves with shut-off elements made of different materials has been investigated experimentally.

The value of the parameter of the mass of the shut-off element at which the optimal mode of operation of the pump is achieved.

References

1. Parfyonov EP (1972) Determination of the performance of piston mortars. Mekh. tools and finishing machines: information Scientific-Technical Sat, vol 4, pp 12–13. TsNIITEstroymash
2. Korobko B, Vasyliev IE (2017) Test method for rheological behavior of mortar for building work Acta mechanica et automatica 11/3(41):173–177. https://doi.org/10.1515/ama-2017-0025
3. Korobko B, Vasiliev A, Rogozin I (2015) The analysis of mixture kinematics in the mixer body frame with a screw elevator with variable generatrix. Eastern-Eur J Enterp Technol 3(7):48–52. https://doi.org/10.15587/1729-4061.2015.4305348-52
4. Mortelpumpen und ihre Entwicklung (1969) Fordern und Heben, no 15 (Germany)
5. EP 0200026, INT. Cl. 4 F 04 B 43/12, 15/02. Neumuller pumps Walter, Sturmer Gerhard. 10.12.1986. Patentblatt 86/45
6. Rohozin I, Vasyliev O, Pavelieva A (2018) Determination of building mortar mixers effectiveness. Int J Eng Technol 7(3.2) (S.I. 2):360–366. https://doi.org/10.14419/ijet.v7i3.2.14553
7. Shapoval MV, Virchenko VV, Skoryk MO, Shpilka AM (2019) Improving the efficiency of the pump by using a hydraulic actuator. In: Collection of scientific papers of the II international Ukrainian-Azerbaijan conference "building innovations—2019", 23–24 May 2019, pp 202–205. PoltNTU, Poltava
8. Emelyanova IA, Shapoval MV (2017) Determination of productivity and volumetric efficiency of the mortar pump, depending on the geometric parameters of the suction chamber and the compensators of various design solutions. Sci Bull Constr 88(2):195–203
9. Kukoba AT, Vasilyev AV (2000) Investigation of the volumetric efficiency of a hydraulic drive mortar. In: Collection of scientific works (branch mechanical engineering, construction, vol 5, pp 19–24. Polt. state. tech. Yuriy Kondratyuk. PDTU, Poltava
10. Kukoba AT, Vasilyev AV, Yakubtsov OM (2000) The impact of the law on the piston against capacious efficiency pump. In: Collection of scientific works (branch engineering, construction, vol 6, pp 12–17. Polt. state. tech. Yuriy Kondratyuk. Part 1. PDTU, Poltava
11. Kukoba AT, Korobko BO, Vasilyev AV (2000) Changing the volume of the mortar mixture during pumping with a solution pump. Mechanization of Construction, 3
12. Shapoval MV (2013) Analysis of the effect of flow pressure on the volumetric pump efficiency. In: Collection of scientific works sectoral mechanical engineering, construction, vol 1, no 36, pp 19–204. PoltNTU, Poltava
13. Korobko B (2016) Investigation of energy consumption in the course of plastering machine's work. Eastern Eur J Enterp Technol 4(8–82):4–11. https://doi.org/10.15587/1729-4061.2016.73336
14. Korobko B, Virchenko V, Shapoval M (2018) Feed solution in the pipeline aith the compensators mortar pump of various design solutions pressure pulsations degree determination. Int J Eng Technol (UAE) 7(3):195–202. https://doi.org/10.14419/ijet.v7i3.2.14402

15. Korobko B, Khomenko I, Shapoval M, Virchenko V (2020) Hydraulic single pump with combined higher volume compensator operation analysishttps://doi.org/10.1007/978-3-030-42939-3_12
16. Korobko B, Zadvorkin D, Vasyliev I (2017) Study of the operating element motion law for a hydraulic-driven diaphragm mortar pump. Eastern Eur J Enterp Technol 4(7–88):25–31. https://doi.org/10.15587/1729-4061.2017.106873