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Improved mathematical model of the hydraulic drive of the garbage truck's sealing plate mechanism taking into account the wear of its hydraulic cylinder

O.V. Bereziuk[1] 0000-0002-2747-2978, **V.I. Savulyak**[1] 0000-0002-4278-5155, **V.O. Kharzhevskyi**[2] 0000-0003-4816-2781, **A.Ye. Alekseiev** 0009-0009-0485-9414

[1] *Vinnytsia National Technical University, Ukraine*

[2] *Khmelnytskyi National University, Ukraine*

E-mail: berezyukoleg@i.ua

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Abstract

This article is dedicated to the improvement of the mathematical model of the hydraulic drive of the mechanism of the garbage truck's sealing plate, taking into account the wear of the hydraulic cylinder. An improved nonlinear mathematical model of the operation of the hydraulic drive of the garbage truck's sealing plate mechanism is proposed, which takes into account the wear of the hydraulic cylinder and allows to numerically study the dynamics of the drive and determine that taking into account the wear of the hydraulic cylinder significantly affects the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism. This study of the mathematical model was carried out using the fourth-order numerical Runge-Kutta-Felberg method with an adaptive integration step. Graphical dependencies were plotted to compare changes in the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism without taking into account the wear of the hydraulic cylinder and with taking into account the wear. It has been established that the creation of a linearized mathematical model of the hydraulic drive of the garbage truck's sealing plate mechanism, taking into account the wear of the hydraulic cylinder, and its analytical solution in order to obtain dependencies for an improved methodology for engineering calculations require further research.

Keywords: wear, wear rate, hydraulic cylinder, mechanism, sealing plate, garbage truck, pressing force, municipal solid waste, mathematical model.

Introduction

One of the key tasks of mechanical engineering is to increase the wear resistance and reliability of machine actuators [1, 2], in particular utility machines, which is mostly equipped with hydraulic actuators of working bodies [3]. One of the leading technologies for the primary processing of municipal solid waste (MSW), aimed at reducing the cost of its transportation and minimizing the negative impact on the environment, is waste compaction directly during loading into a garbage truck. Solid waste is compacted in the garbage truck using a sealing plate driven by a hydraulic cylinder. This hydraulic cylinder is subject to intense wear due to the large number of operating cycles and high compression forces caused by the nonlinear compression characteristics of MSW. Hydraulic cylinders are usually made of alloy steel, and it is advisable to use wear-resistant coatings to increase their operational durability. Improving the mathematical model of the hydraulic drive of the garbage truck's sealing plate mechanism, taking into account the wear of the hydraulic cylinder, contributes to more efficient planning of upgrading, renewal, maintenance, and repair of municipal utility machines.

Analysis of recent research and publications

In the paper [3], the pressure losses were determined on the basis of computer modeling of hydrodynamic processes of the working fluid flow through the water seal. To reduce them, structural changes to the water seal were proposed that did not affect its functionality. This made it possible to reduce the pressure loss in the working part of the hydraulic distributor, which, in turn, reduces the overall energy losses in the hydraulic drive system.

The scientific article [4] discusses the peculiarities of the wood chip pressing process in screw machines and analyzes the processes occurring in different parts of the screw. The established dependencies make it possible to calculate the loads on the screw turns and determine the required power for pressing. In addition, the degree of raw material heating and specific energy consumption during the pressing process were determined.

In the article [5], the exponential dependence of changes in the rate of wear of the working hydraulic cylinder of the mechanism of the garbage truck's sealing plate was established, depending on the pressing force. Taking this dependence into account allows to improve maintenance and repair planning and to increase the efficiency of garbage trucks in general. For better understanding of the process, a graphical dependence of the change in the wear rate of the working hydraulic cylinder of the garbage truck's sealing plate mechanism on the pressing force was plotted, which confirmed the sufficient convergence of the obtained dependence. It was determined that for a Ukrainian-made garbage truck of the serial model KO-436, the wear rate of the working hydraulic cylinder of the mechanism of the garbage truck's sealing plate, according to the obtained dependence, will be 0.257 μm/h, and an increase in the pressing force from 30 MN to 150 MN leads to a decrease in the wear rate of the working hydraulic cylinder of the hydraulic press mechanism by 3.6 times. This effect is explained by the peculiarities of contact processes between the working surfaces and the operating conditions of the mechanism at different load levels.

According to the study [6], among the main components of garbage trucks with side loading of MSW, the hydraulic system has the lowest working resource before failure, which is the main factor in the increased wear and tear of these vehicles. According to the results of research [7], the structure and most common causes of failures of the hydraulic equipment of garbage trucks were determined: hydraulic cylinders – 34.92 % (wear of cuffs, seals, rod; rupture of the piston mounting nut; rod bending; mechanical damage), hydraulic pumps – 16.40 % (casing wear, gear wear, squeezing of seals, casing cracks), pipelines and hoses – 15.34 % (hose breaks, pipeline wear), hydraulic distributors – 13.23 % (wear of seals and spools, casing cracks).

The analysis of the causes of typical technical failures of garbage trucks presented in [8] showed that a significant number of failures (about 45 %) are related to hydraulic drive failures. The main factors of these failures are manufacturing defects related to the usage of low-quality components, as well as significant fluctuations in the loads on the actuators. The study of the causes of actuators' failures showed that the main failures are caused by heat treatment defects and deviations from the design dimensions during manufacturing (35%), errors during assembling, adjustment and tightening of threaded connections (30%), as well as poor welding (30%). It was found that most failures (80-90 %) are related to the wear and corrosion of the working surfaces of parts, and failure occurs when a critical level of degradation is reached, i.e. when a machine or its component reaches the limit of its technical condition. In particular, up to 28% of all hydraulic drive component failures are related to hydraulic cylinders, caused by wear of mating surfaces, deformation of the rod and cylinder during operation. The durability analysis showed that the average time between failures of hydraulic drive elements, including hydraulic cylinders, is only about one-third of their maximum service life. In many cases, the manufacturer's service life is reached not more than 45-55%. The highest percentage of hydraulic cylinder failures at the initial stage of operation or after repair relates to rods (31%) and sealing cuffs (42%). In addition, the analysis of failures of hydraulic system elements showed that the main manifestation of failures is the loss of external and internal tightness caused by contamination of the working fluid, which leads to malfunctioning of the units.

The above data are consistent with the results published in [9], where the main causes of garbage truck's hydraulic system failures caused by wear are identified: for a hydraulic pump – wear of gears; for hydraulic cylinders – wear of cuffs, seals, and rod; for a hydraulic distributor – wear of seals and spools; for hoses – wear of pipelines. In addition, the paper establishes adequate dependencies of wear of garbage truck tires on the front and rear axles, depending on the transported mass of solid waste and the vehicle mileage, according to the Fisher criterion. According to the Student's criterion, it was determined that the weight of the transported solid waste has the greatest impact on the wear of tires on both the front and rear axles, while the mileage of the garbage truck has the least impact. The dependences of the number of garbage truck trips before reaching the maximum permissible tire wear on the front and rear axles were also obtained.

Paper [10] provides a detailed review of the main causes of garbage truck failures, which shows that the leading factors in the occurrence of failures are external and internal leaks in hydraulic systems. In particular, the percentage of the external leaks is about 48% of all reported failures and are caused mainly by damage to hoses and pipelines, as well as leaks in the seals of hydraulic cylinders and other units. These damages lead to leaks of working fluid, which negatively affects the operation of the entire hydraulic system, causing a decrease in its efficiency and increasing the risk of serious breakdowns. In addition, an important and common cause of failure is internal leakage, which is approximately 36% of the total number of failures. Internal leakage occurs due to a leak between the working cavities of hydraulic components, which leads to the flow of working fluid into non-working areas and a decrease in system pressure. Such problems are often observed in important elements of the hydraulic system: spool valves, safety and check valves, hydraulic cylinders, and hydraulic pumps. These units are important to the normal functioning of garbage trucks, so their malfunctions due to internal leaks significantly affect the overall performance and reliability of the equipment.

In the paper [11], it was found out that the “conical” wear of the hydraulic cylinder rod in the range of 0.2 to 0.4 mm in length before the first overhaul causes a decrease in system pressure by 7.2 %, an increase in specific fuel consumption by 11.4 %, and an increase in the content of carbon monoxide in exhaust gases by 26 %. Increasing of the rod wear at the working area to 0.6-0.7 mm leads to a 13.4% drop in hydraulic system pressure, a 21.3% increase in specific fuel consumption, and an increase in exhaust gas toxicity from 25% to 59%, which exceeds the permissible limits. The maximum permissible wear of the geometric parameters of the hydraulic cylinder rod of the hydraulic drive of construction and road machines is proposed to be less than 0.4 mm. In addition, it was found that rod wear negatively affects the physical and chemical properties of the working fluid, increasing the content of iron and impurities in it by two times, which leads to the need for more frequent replacement and increase in cost. This significantly reduces the efficiency and durability of the hydraulic actuator, shortening its service life in construction and road machines.

In the paper [12], it is stated that the wear of sealing elements in hydraulic systems leads to the gradual penetration of hydraulic fluid into non-working cavities of hydraulic machines. Although this process is not always noticeable externally, it causes unproductive power losses of the hydraulic drive, which, in turn, leads to excessive fuel and lubricant consumption and reduced power of the working bodies. Power losses due to seal wear can cause non-optimal hydraulic motor operation, which negatively affects the overall efficiency of the hydraulic drive. The study considers the mechanical system "hydraulic cylinder – sealed piston – compressed hydraulic fluid", where the dependence of the efficiency of the hydraulic cylinder on the value of the leakage is established. The results of piston deflection when using VMGZ working fluid are also determined and the mechanism of fluid flow through the hydraulic cylinder seal is analyzed.

The authors of the article [13], while analyzing observations of garbage trucks, found that the largest number of failures relate to the wear and corrosion of the working surfaces of the parts of working equipment. Failures of hydraulic cylinders caused by wear of the working surfaces of the mating surfaces, deformations of the rod and cylinder during operation are found to be 32 % of all breakdowns of hydraulic drive parts. This is due to uneven loading of the body and abrasive wear in the difficult operating conditions of the garbage truck. Studies of the causes of failures have shown that the main cause is wear on the working surfaces of key hydraulic drive parts, including spools and hydraulic distributor housings, hydraulic cylinder rods, etc. The main factor of wear is water-abrasive damage, which occurs due to untimely replacement of the hydraulic fluid and the use of low-quality or worn sealing elements, such as hydraulic cylinder seals. This leads to dust and wear products entering the sliding zone, which accelerates the wear of working surfaces. One of the most promising methods for restoring worn parts in the paper is chrome plating in a cold self-regulating electrolyte, which produces high quality chrome coatings with high performance.

In the article [14], a nonlinear mathematical model described by a system of differential equations with appropriate boundary conditions was proposed and studied in detail, which characterizes the operation of the hydraulic drive of the mechanism of the garbage truck’s sealing plate, in particular for the static method of solid waste compression – an important stage of primary waste processing. However, despite the high accuracy and detail of the model, it does not take into account the impact of wear on the power hydraulic cylinder, which is one of the key elements of the hydraulic drive. Ignoring this factor may limit the application of the model for long-term forecasting of the mechanism's effectiveness in real operating conditions, where hydraulic cylinder wear significantly affects the performance and reliability of the system.

However, as a result of the analysis of known publications, the authors did not find a specific mathematical model describing the operation of the hydraulic drive of the garbage truck’s sealing plate mechanism taking into account the wear of the hydraulic cylinder.

Aims of the article

Improvement of the mathematical model of the hydraulic drive of the mechanism of the garbage truck’s sealing plate taking into account the wear of the hydraulic cylinder.

Methods

Fig. 1 shows a calculation scheme of the garbage truck’s operation at the technological operation of static compaction of MSW [14], with the following structural elements and values: PP – pressing plate; HC – hydraulic cylinder; HD – hydraulic distributor; P – hydraulic pump; SV – safety valve; F – filter; T – working fluid tank. The diagram also shows the following basic geometric, kinematic, and power parameters: p_1, p_2, p_3, p_4 – pressures at the pump outlet, hydraulic cylinder inlet, hydraulic cylinder outlet, and filter inlet, respectively; W_1, W_2, W_3, W_4 – volumes of pipelines between the pump and hydraulic distributor, hydraulic distributor and hydraulic cylinder inlet, hydraulic cylinder outlet and hydraulic distributor, hydraulic distributor and filter; Q_P – actual pump flow rate; S_P – cross-sectional area of the distributor opening; S_f – surface area of the filter element; k_f – specific filter capacity (not shown in the diagram); μ_d – dynamic viscosity coefficient (not shown in the diagram); D, d – diameters of the piston and rod; G_p – weight of the pressing plate; G_c – weight of the hydraulic cylinder; G_{W1} – weight of the waste above the pressing plate; G_{W2} – weight of the waste outside the pressing plate; F_{FR} – friction force between the pressing plate and the guides; F_{TW} – the friction force between the MSW and the body; F_C – the force developed by the hydraulic cylinder; h_1, h_2 – the heights of the bottom and top of the press plate; b – the width of the press plate (not shown in the diagram); δ – the thickness of the press plate; α is the angle of inclination of the press plate; x – the displacement of the press plate.

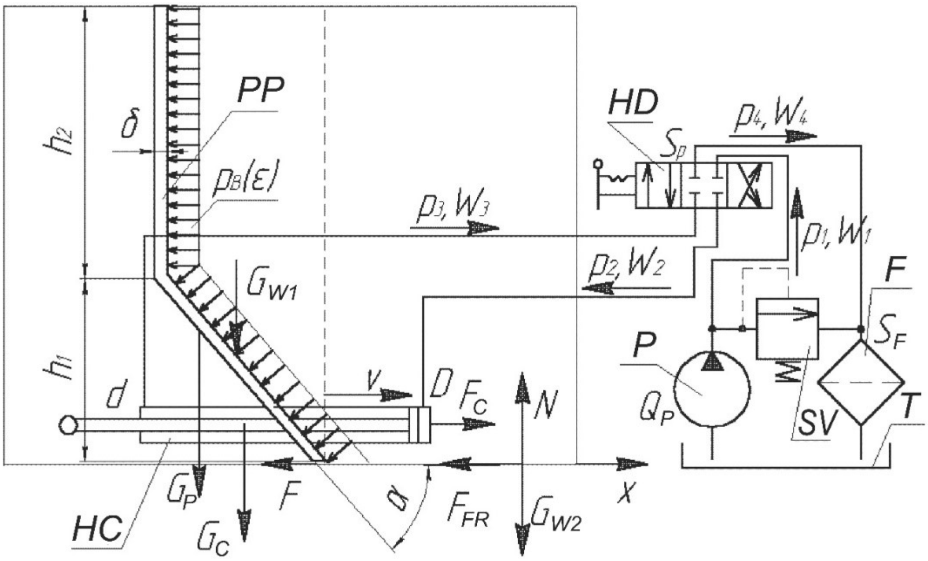


Fig. 1. Design diagram of the hydraulic drive of the pressing plate for static compaction of solid waste

The operation of the hydraulic actuator in the technological operation of static compression of MSW can be described by the following system of differential equations (1-5) with the corresponding boundary conditions (6) [14]:

$$\begin{cases} Q_P = \mu S_P \sqrt{\dfrac{2(p_1 - p_2)}{\rho_{WF}}} + \sigma(p_1 - p_2) + KW_1 \dfrac{dp_1}{dt}; & (1) \\ \mu S_P \sqrt{\dfrac{2(p_1 - p_2)}{\rho_{WF}}} = \dfrac{dx}{dt} S_{C1} + \sigma(p_2 - p_3) + KW_2 \dfrac{dp_2}{dt}; & (2) \\ \dfrac{dx}{dt} S_{C2} = \mu S_P \sqrt{\dfrac{2(p_3 - p_4)}{\rho_{WF}}} + \sigma(p_3 - p_4) + KW_3 \dfrac{dp_3}{dt}; & (3) \\ \mu S_P \sqrt{\dfrac{2(p_3 - p_4)}{\rho_{WF}}} = k_f \dfrac{p_4}{\mu_Д} S_f + \sigma p_4 + KW_4 \dfrac{dp_4}{dt}; & (4) \\ p_2 S_{C1} - p_3 S_{C2} = m_P \dfrac{d^2x}{dt^2} + \beta \dfrac{dx}{dt} + \left[8{,}661 \cdot 10^4 + 2{,}037 \cdot 10^7 \left(\dfrac{x}{x_{\max}} \right)^{12} \right] S_{P1} + F_{FR} + F_{TW}; & (5) \\ 0 \le \{p_1, p_2, p_3, p_4\} \le p_{zk};\ 0 \le x \le x_{\max}. & (6) \end{cases}$$

The paper [5] determines the dependence of changes in the wear rate of the working hydraulic cylinder of the mechanism of the garbage truck's sealing plate depending on the pressing force

$$\begin{aligned} v_{u.} &= \frac{du}{dt} = 0{,}2575 \mathrm{e}^{-0{,}01047 F_{pr}[MH]} = 0{,}2575 \mathrm{e}^{-0{,}01047 \cdot 10^{-6} F_{pr}[H]} = \\ &= 0{,}2575 \mathrm{e}^{-1{,}047 \cdot 10^{-8} p_2 S_{C1}} [\mu\text{m/h}] = 7{,}153 \cdot 10^{-7} \mathrm{e}^{-1{,}047 \cdot 10^{-8} p_2 S_{C1}} [\mu\text{m/sec}]. \end{aligned} \tag{7}$$

where v_u – the wear rate of the hydraulic cylinder, μm/h; u – the wear of the hydraulic cylinder, μm; F_{pr} – the pressing force, MN.

The coefficient of losses of the working fluid (WF) due to flow from a high-pressure area to a low-pressure area, taking into account the wear of the hydraulic cylinder, can be determined by the formula [15].

$$\sigma = \frac{\pi D \delta^3}{12 \nu \rho_{WF} l} = \frac{\pi D \left(\delta_0 + 10^{-6} u\right)^3}{12 \nu \rho_{WF} l} \ [\text{m}^5/(\text{N}\cdot\text{sec})], \tag{8}$$

where δ_0 – the nominal size of the gap, m; ν – the kinematic viscosity WF of the working fluid, m²/sec; ρ_{WF} – the density of the working fluid, kg/m³; l – the length of the annular gap, m.

To study an improved nonlinear mathematical model of the operation of the hydraulic drive of the mechanism of the garbage truck's sealing plate, taking into account the wear of its hydraulic cylinder in the form of a system of ordinary nonlinear differential equations with corresponding boundary conditions, the Runge-Kutta-Felberg numerical method of the 4th order with a variable integration step was used.

Results

After substituting formula (8) into differential equation (2) and taking into account differential equation (7), the improved nonlinear mathematical model of the operation of the hydraulic drive of the garbage truck's sealing plate mechanism, taking into account the wear of its hydraulic cylinder, can be written as follows:

$$\begin{cases} Q_P = \mu S_P \sqrt{\dfrac{2(p_1 - p_2)}{\rho_{WF}}} + \sigma(p_1 - p_2) + K W_1 \dfrac{dp_1}{dt}; & (10) \\ \mu S_P \sqrt{\dfrac{2(p_1 - p_2)}{\rho_{WF}}} = \dfrac{dx}{dt} S_{C1} + \dfrac{\pi D \left(\delta_0 + 10^{-6} u\right)^3}{12 \nu \rho_{WF} l} (p_2 - p_3) + K W_2 \dfrac{dp_2}{dt}; & (11) \\ \dfrac{dx}{dt} S_{C2} = \mu S_P \sqrt{\dfrac{2(p_3 - p_4)}{\rho_{WF}}} + \sigma(p_3 - p_4) + K W_3 \dfrac{dp_3}{dt}; & (12) \\ \mu S_P \sqrt{\dfrac{2(p_3 - p_4)}{\rho_{WF}}} = k_f \dfrac{p_4}{\mu_Д} S_f + \sigma p_4 + K W_4 \dfrac{dp_4}{dt}; & (13) \\ p_2 S_{C1} - p_3 S_{C2} = m_P \dfrac{d^2 x}{dt^2} + \beta \dfrac{dx}{dt} + \left[8{,}661 \cdot 10^4 + 2{,}037 \cdot 10^7 \left(\dfrac{x}{x_{\max}} \right)^{12} \right] S_{P1} + F_{FR} + F_{TW}; & (14) \\ \dfrac{du}{dt} = 7{,}153 \cdot 10^{-7} \mathrm{e}^{-1{,}047 \cdot 10^{-8} p_2 S_{C1}}; & (15) \\ 0 \le \{p_1, p_2, p_3, p_4\} \le p_{zk};\ 0 \le x \le x_{\max}. & (16) \end{cases}$$

A comparison of changes in the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism without taking into account wear and taking into account the wear of the hydraulic cylinder is shown in Fig. 2. The graphical dependencies shown in Fig. 2 are obtained for the drive parameters corresponding to the serial model of the KO-436 garbage truck that is manufactured by "Turbivskyi Machine-Building Plant" (Public joint stock company «ATEKO»): W_1= 1.48 l; W_2= 1.59 l; W_3= 1.59 l; W_4= 0.3 l; S_p= 5.02· 10^{-5} m²; S_f= 3.49· 10^{-2} m²; k_f= 6.13· 10^{-9} m; μ_e= 1.63· 10^{-2} N· sec/m²; ν = 1.83· 10^{-5}m²/sec; ρ_{WF}= 890 kg/m³; δ_0= 0.136 mm; l = 35 mm; $x_{\max}$ = 900 mm; m_p= 54 kg; β = 50 N·sec/m; σ = 9.24 10^{-11} m⁵ /(N·sec); S_{C1}= 9.503· 10^{-3} m²; S_{C2}= 3.142· 10^{-3} m²; S_{P1}= 1.019 m²; D = 110 mm; d = 90 mm; F_{TP} = 247.7 N; F_{TV}= 718 N; p_{zk} = 10 MPa; t_0= 0 c; x_0= 0 m; p_{10} = 0 MPa; p_{20}= 0 MPa; p_{30} = 0 MPa; p_{40} = 0 MPa.

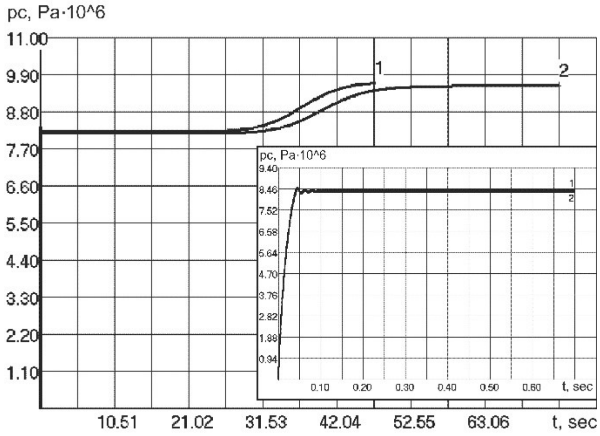
The calculations were performed with an integration step h = 10^{-4} sec and a relative error ε = 10^{-16}. The stability of the solution to the system of differential equations was ensured by checking the identity of the results obtained at the values of the integration steps h and $h/2$.

In the blank field of the Figs. 2a and 2b it is shown the graphs of transient processes during the startup of the hydraulic drive of the garbage truck's sealing plate mechanism. As it can be seen from the Fig. 2, taking into account the wear of the hydraulic cylinder in the improved mathematical model significantly affects the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism.

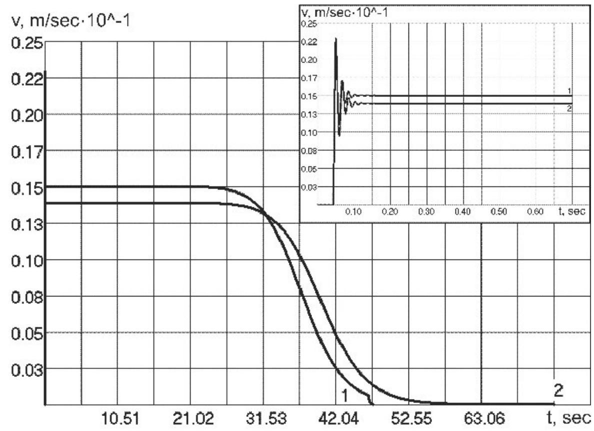
The construction of a linearized mathematical model of the operation of the hydraulic drive of the garbage truck's sealing plate mechanism, taking into account the wear of the hydraulic cylinder, and its analytical solution in order to obtain dependencies for an improved methodology for engineering calculations require further research.

Conclusions

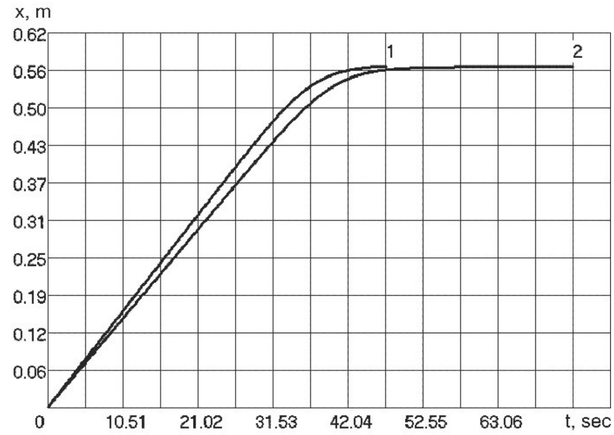
An improved nonlinear mathematical model of the operation of the hydraulic drive of the garbage truck's sealing plate mechanism is proposed, which takes into account the wear of the hydraulic cylinder and allows to numerically study the dynamics of this drive and determine that taking into account the wear of the hydraulic cylinder significantly affects the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism. Graphical dependencies have been plotted to compare changes in the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism without taking into account the wear of the hydraulic cylinder and with taking into account the wear.



a)



b)



c)

Fig. 2. Comparison of changes in the main parameters of the hydraulic drive of the garbage truck's sealing plate mechanism: 1 – without taking into account the wear of the hydraulic cylinder; 2 – taking into account the wear of the hydraulic cylinder: a) change in pressure in the hydraulic cylinder; b) speed of the sealing plate; c) movement of the sealing plate

It has been also established that the construction of a linearized mathematical model of the hydraulic drive of the garbage truck's sealing plate mechanism, taking into account the wear of the hydraulic cylinder, and its analytical solution in order to obtain dependencies for an improved methodology for engineering calculations require further research.

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Березюк О.В., Савуляк В.І., Харжевський В.О., Алексеєв А.Є. Удосконалена математична модель роботи гідроприводу механізму ущільнюючої плити сміттєвоза із урахуванням зносу його гідроциліндра.

Дана стаття присвячена удосконаленню математичної моделі роботи гідроприводу механізму ущільнюючої плити сміттєвоза із урахуванням зносу гідроциліндра. Запропонована удосконалена нелінійна математична модель роботи гідроприводу механізму ущільнюючої плити сміттєвоза, яка ураховує знос гідроциліндра і дозволяє чисельно дослідити динаміку даного приводу та визначити, що врахування зносу гідроциліндра суттєво впливає на основні параметри гідроприводу механізму ущільнюючої плити сміттєвоза. Дане дослідження математичної моделі здійснювалося із застосуванням чисельного методу Рунге–Кутта–Фельберга четвертого порядку з адаптивним кроком інтегрування. Побудовано графічні залежності для порівняння зміни основних параметрів гідроприводу механізму ущільнюючої плити сміттєвоза без урахування зносу гідроциліндра та з урахуванням зносу. Встановлено, що побудова лінеаризованої математичної моделі роботи гідроприводу механізму ущільнюючої плити сміттєвоза із урахуванням зносу гідроциліндра та її аналітичне розв'язання з метою отримання залежностей для удосконаленої методики інженерних розрахунків вимагають проведення подальших досліджень.

Ключові слова: знос, швидкість зношування, гідроциліндр, механізм, ущільнююча плита, сміттєвоз, зусилля пресування, тверді побутові відходи, математична модель.