***ISSN 2079-1372 Problems of Tribology**, V. 31, No 1/119-2026, 62-71*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2026-119-1-62-71

Improved algorithm for engineering calculations of the parameters of a container tipping mechanism in a garbage truck taking into account the wear of friction pairs

O.V. Bereziuk [1] 0000-0002-2747-2978, **V.I. Savulyak** [1] 0000-0002-4278-5155, **V.O. Kharzhevskyi** [2] 0000-0003-4816-2781, **S. Cv. Ivanov** [3] 0000-0002-7719-6086, **V.Ye. Yavorskyi** [1] 0009-0002-8724-3963

[1] Vinnytsia National Technical University, Ukraine
[2] Khmelnytskyi National University, Ukraine
[3] Technical University Sofia, Branch Plovdiv, Bulgaria
E-mail: berezyukoleg@i.ua

Received: 20 January 2026: Revised 07 February 2026: Accept: 20 February 2026

Abstract

The article is dedicated to the development of the scientifically grounded improved method, based on the analysis of scientific literature sources, for the design calculation of the parameters of a mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account friction wear, in order to determine its main geometric, force, and speed parameters. The drive of the working parts of the mechanism for tipping a container with municipal solid waste into a garbage truck is hydraulic, with a power source from the garbage truck's pump station. The usage of the proposed improved methodology for the engineering calculation of the parameters of the mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs, allows significant reduction in design time and avoids unnecessary costs for labor-intensive experimental and theoretical research. Using the proposed scientifically based improved method of design calculation of the parameters of the mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs, its main geometric, force, and speed parameters have been determined. It has been established that the development of an improved methodology for the design calculation of the parameters of the mechanism for rotating the manipulator lever during the loading of municipal solid waste into a garbage truck, taking into account the wear of friction pairs, requires further research.

Keywords: algorithm, project calculation methodology, wear accounting, hydraulic drive, wear, friction units, container tipping mechanism, garbage truck, municipal solid waste.

Introduction

Among the main directions of development of modern municipal engineering in Ukraine, tasks related to the improvement of mobile manipulator-type machines, in particular garbage trucks, have an important role [1]. Within this area, issues related to improving the wear resistance, reliability, and durability of machine elements are of particular importance, since these indicators determine the efficiency of technical equipment operation, contribute to reducing repair and maintenance costs, and ensure an increase in the service life of equipment under conditions of intensive use [2, 3]. In Ukraine, the collection and transportation of municipal solid waste (MSW) to facilities for further processing or disposal is mainly carried out using body garbage trucks [4, 5]. The key functional element of such machines is loading devices [6-8], designed as manipulator mechanisms [9-13] with hydraulic drive [14, 15]. Currently, there are about 3,700 garbage trucks in operation, which, in addition to transporting solid waste, perform compaction operations. This significantly reduces transportation costs and the area of landfills required for solid waste disposal, which is of great economic and environmental importance. During the technological operation of loading MSW into the body of a garbage truck, friction units, primarily hinge joints and hydraulic cylinders of the manipulator mechanism, are subjected to significant mechanical loads. The increased wear and tear on these components is due to a combination of factors, including the significant weight of waste containers, which can reach 500 kg, the operation of mechanisms in reverse mode with reciprocating movements, and the large number of work cycles performed during a single trip. In addition, operating conditions are complicated by operational factors, in particular significant fluctuations in relative humidity and temperature, as well as increased dusty environment, the combined effect of which causes intensified wear of working elements, which, in turn, negatively affects the reliability and durability of garbage trucks. The deterioration of the operational properties of the materials of the parts or an insufficient level of lubrication cause an increase in friction forces in the hinge joints of the manipulator mechanism, resulting in an increase in the level of vibrations in the system, which negatively affects its dynamic stability and reduces the ability of the mechanism to withstand significant loads under conditions of reversible friction. Intensive wear of friction components not only reduces the efficiency of the manipulator mechanism of the garbage truck, but also creates additional risks to the safe operation of the equipment. As a result, emergency operating modes may occur, posing a health hazard to service personnel and potentially causing negative environmental consequences in the event of uncontrolled spillage or leakage of solid waste. According to the provisions of Resolution No. 265 of the Cabinet of Ministers of Ukraine [16], one of the priority areas for the development of the public utilities sector is the introduction of modern, highly efficient garbage trucks, which are considered a key element of the system of technical means designed for the collection, transportation, and primary processing of solid waste. The usage of modern equipment not only optimizes logistics processes and reduces operating costs, but also contributes to the comprehensive solution of topical environmental problems related to the waste management system, and also ensures the reliability and effectiveness of public utility companies, which is of strategic importance for the sustainable development of populated areas. The planning of the renewal, maintenance, and repair of garbage trucks is facilitated by the development of an improved methodology for the design calculation of the parameters of the mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs.

Analysis of recent research and publications

Scientific paper [17] presents the results of structural analysis of garbage truck parts subject to intensive wear. The study described in article [18] proposes a method for diagnosing failures caused by wear of the sealing elements of the hydraulic cylinder and the presence of internal working fluid leaks, based on the usage of energy characteristic fusion. The study [19] developed the design of a robotic manipulator, created its 3D model in SOLIDWORKS, and performed a motion analysis. At the structural optimization design stage, key parameters, in particular the stresses and deformations of the manipulator, were evaluated comprehensively, and target functions and constraints for improving its design were determined. This approach reduces the probability of manipulator failure during prolonged heavy-duty operation and ensures more efficient interaction with other garbage truck systems, increasing the overall productivity of MSW collection and transportation processes.

A mathematical model that allows to determine the optimal geometric parameters of the manipulator's structural elements, taking into account the maximum boom reach, lifting capacity, and other kinematic characteristics of the machine, was developed in [20]. This model is an important tool for design engineers, as it ensures a rational choice of dimensional parameters of structural elements in order to improve the efficiency of the manipulator and ensure its reliability in operation. Particular attention is paid to the characteristics of hinge joints operating in a cyclic mode typical for manipulator-type machines. It has been established that under such conditions, the formation of a normal hydrodynamic friction regime is impossible, since the lubrication process occurs mainly in semi-dry or boundary friction modes. This leads to increased requirements for the properties of parts materials, the quality of surface treatment, and the efficiency of the lubrication system, since these factors determine the wear resistance and durability of hinge assemblies in real operating conditions. Contrary to the stable hydrodynamic friction regime, the operation of sliding bearings under semi-dry or boundary friction conditions is accompanied by more intense wear of contact surfaces, which leads to a gradual loss of kinematic accuracy, the occurrence of additional dynamic and shock loads and vibrations, which contribute to the development of fretting corrosion and premature failure of parts. To reduce friction forces, it is proposed to use special coatings for the contact elements of joints, in particular lead, phosphate, and indium coatings. It has been proven that the intensity of contact wear can be significantly reduced by using lubricants based on oils and fats, as well as consistent lubricants, which at a temperature of 25 °C acquire a thick, ointment-like consistency. In addition, the usage of phosphate and anodic metal coatings has been shown to be effective in improving grease retention on friction surfaces, increasing the efficiency and durability of components.

A method for optimizing the operation of a robotic workspace, which involves adjusting the position of the robot manipulator within the working area for programs with a fixed end-point motion trajectory, is proposed in the article [21]. The main aim of the study was to reduce the total wear of the manipulator joints and prevent their uneven loading when individual joints are subjected to greater mechanical stress than others. Wear was assessed by approximating the integral of the mechanical work of each joint along the entire trajectory, which was determined by the angular velocities and applied torques. The approach was based on dynamic modeling, which allows calculating the torques and rotational speeds of the joints in different positions of the robot. The results of the study showed that the optimal location of the manipulator base reduces the overall wear of its joints by 22-53%, depending on the configuration of the motion trajectory.

A detailed analysis of the main types of wear of hinge joints used in forestry manipulator designs is presented in [22]. The results of the study made it possible to identify promising areas for improving their wear resistance, which can be used by design engineers to extend the working life of components depending on specific operating conditions and technical requirements. Particular attention is paid to the fact that manipulator machines mostly operate in difficult climatic conditions with sharp fluctuations in ambient temperature, which significantly affects the stability of the properties of lubricants and the performance characteristics of structural materials of joints. At low temperatures, friction pair materials lose their plasticity, their brittleness increases, their yield strength decreases, and the stiffness of working surfaces increases, which complicates movement processes and the annihilation of dislocations in the crystal lattice, accompanied by exoelectron emission and accelerated wear. In addition, the properties of lubricants change: at low temperatures, they can lose their fluidity, transition to a solid state, or significantly increase their viscosity, which reduces their ability to form a protective film and increases the intensity of wear. During the summertime, when the ambient temperature is high, lubricants overheat, lose their viscosity, and can spontaneously leak from the friction zone, which negatively affects the lubrication and cooling of working surfaces, increases the risk of overheating of contacting elements, and accelerates the wear of hinge assemblies. To prevent these effects, it is recommended to use special sealing devices that can simultaneously protect the hinge joints from dust, moisture, and aggressive impurities, as well as retain the lubricant in the friction zone. Studies have confirmed the effectiveness of integrating contact and labyrinth sealing elements into the design of joints, which, thanks to their specific design, provide reliable protection of assemblies from negative factors of the operating environment and increase the service life of manipulators.

The study [23] demonstrates that when designing and creating new promising hinge joint designs, it is advisable to use a comprehensive approach to selecting scientific and engineering solutions. This is due to the fact that the performance of such assemblies is simultaneously influenced by a significant number of related factors, including design features, properties of friction pair materials, load conditions, lubrication modes, and the nature of the operating environment. Taking into account the combined effect of these parameters creates the prerequisites for the formation of fundamentally new design solutions capable of ensuring an increased level of reliability and durability of the hinge assemblies of forestry machine manipulators. The use of a comprehensive approach makes it possible to directly influence not only the mechanical properties of joints, such as strength and rigidity, but also their tribotechnical characteristics, in particular the coefficient of friction, wear intensity, and stability of operation under variable load conditions. In addition, the implementation of modern design solutions contributes to the optimization of the thermal regime of the joints, which is essential for reducing thermal deformations and preventing premature destruction of materials. As a result, this approach ensures increased efficiency of logging equipment operation, reduced maintenance costs, and increased service life of manipulator systems in difficult operating conditions.

In the paper [24], a method for synthesizing the motion trajectory of a manipulator robot is proposed, which takes into account its kinematic characteristics and the degrees of mobility of individual links. In particular, the influence of the rod deflection on the support reactions in the contact zone is considered, which in its physical essence resembles the work of a beam supported by two supports. This approach allows modeling the distribution of force influences on the robot's elements during its operation, including the contact areas of the hydraulic cylinder, rod, and ground bushing. Based on the determined values of contact pressure, it is possible to quantitatively assess the potential wear processes of friction surfaces, predicting their intensity and localization. It has been established that even in conditions where there is no danger of critical destruction of the rod under bending, contact stresses reaching approximately one third of the material's strength limit can significantly accelerate the wear of working surfaces. This is due to the fact that repeated load cycles lead to microdamage, increased local surface roughness, and the development of abrasive and contact wear processes. Additionally, it is taken into account that the specifics of contact pressure formation depend on the opening angle of the rod, its speed of movement, and the sequence of the manipulator's working cycles, which makes it possible to evaluate wear in different operating modes.

The results of the analysis of the design characteristics of the manipulator grippers of body garbage trucks and the assessment of their reliability are presented in scientific article [25]. Based on the research, a computational model of a garbage truck was developed, which is considered as an oscillatory system. The analysis revealed the peculiarities of the garbage truck frame vibrations during operation and the patterns of force formation in the interaction of the "gripper-tank-gripper" system elements. The research found that the greatest loads are on the thrust and rod of the hydraulic cylinder, and their magnitude increases with the increase in container weight. A change in the mass of the garbage truck itself does not affect the magnitude or amplitude of the loads, but changes their frequency characteristics. Operational observations have shown that the main causes of garbage truck failures are wear and corrosion of the working surfaces of equipment parts. In particular, 32% of all hydraulic drive failures occur in hydraulic cylinders. The failures of these units are caused by wear on the contact surfaces of the connections, deformation of the rod and cylinder under the action of operational loads, uneven loading of the body, and abrasive wear in difficult operating conditions. The main factor in hydraulic drive failures is the intensive wear of key components, in particular spools and hydraulic distributor housings, as well as hydraulic cylinder rods. Additional degradation is caused by hydroabrasive damage, which occurs due to delayed replacement of the working hydraulic fluid and the use of low-quality or worn sealing elements, such as hydraulic cylinder seals. This leads to the penetration of dust particles and wear products into the friction zone, which significantly accelerates the destruction of working surfaces. To increase the service life and restore the performance of parts, it is recommended to use cold self-regulating electrolyte chromium plating technology, which provides the formation of chrome coatings with high deposit quality, increased wear resistance, and sufficient productivity. This makes this technology one of the most promising methods for restoring worn hydraulic drive components.

An analytical study of the mathematical model of the process of grinding polymer waste in the grinding chamber of a rotary crusher with continuous classification of the finished product, conducted in [26], provided a detailed understanding of the influence of various technological and design parameters on the performance of the installation. In particular, the study made it possible to determine with high accuracy the particle size distribution of the final product, evaluate the crusher's performance, and analyze energy consumption under variable operating conditions. It was found that the key factors affecting the quality of grinding and the efficiency of the process are the angular velocity of the rotor, the initial size and physical and mechanical properties of the waste, the design parameters of the crusher, in particular the geometry of the chamber and the size of the grid slots, as well as the chamber loading modes. The study showed that changing the angular velocity of the rotor allows optimizing the ratio of productivity and energy consumption, since an increase in speed leads to more intensive crushing of particles, but also increases the specific energy consumption of the process. At the same time, analysis of the influence of the initial size of the waste and the design characteristics of the crusher allows predicting the final particle distribution, determining the optimal parameters for achieving the desired product size, and avoiding overloads in the chamber. Complex evaluation of the loading modes and rotor rotation parameters makes it possible not only to increase the efficiency of the crusher, but also to optimize operating costs and energy consumption, which is an important aspect in the industrial scaling of the polymer waste grinding process.

The article [27] describes an algorithm for numerical and analytical research of dynamic processes in a planar six-bar linkage mechanism of a sewing machine threader. The proposed approach is based on the numerical solution of the differential equation of motion of the mechanism, taking into account its kinematic and dynamic parameters, which allows to describe details of the motion of individual links and determine the change in velocities and accelerations during the working cycle. In addition to analytical calculations, the authors performed computer modeling of the analyzed mechanism in Mathcad, which made it possible to visually reproduce its operation and verify the correctness of the obtained numerical results. The use of a combination of analytical methods and computer modeling made it possible to investigate the influence of design parameters and operating modes on the dynamic characteristics of the threader mechanism. During the simulation, changes in loads in hinge joints were analyzed, and regularities in the distribution of inertial forces arising during the operation of the mechanism were determined. The results of this study can be used to develop a design calculation methodology for optimizing the design of the threader, improving its reliability, and reducing dynamic loads.

In the scientific work [28], on the basis of a detailed analytical study of the mathematical model, the main regularities of the functioning of vibration and vibration-impact machines operating with the usage of a hydraulic pulse drive equipped with a single-stage pulsator valve were established. The developed model made it possible to describe the dynamic processes that occur in the hydraulic system and working parts of the machine, as well as to analyze the nature of pressure pulse formation and their influence on the kinematic and force parameters of vibrational motion. The study identified the relationships between the design parameters of the hydraulic pulse drive, its operating modes, and the dynamic characteristics of the machines, in particular the amplitude and frequency of vibrations, as well as the energy of shock pulses. The obtained results made it possible to establish the conditions for the stable operation of vibrating and vibro-impact machines, to evaluate the effectiveness of using a hydraulic pulse drive in various operating modes, and to formulate recommendations for optimizing the parameters of the pulsator valve in order to increase the productivity, reliability, and energy efficiency of such machines, necessary for creating a methodology for the design calculation of the parameters of these machines.

The article [29] proposes an improved nonlinear mathematical model of the operation of the hydraulic drive of the mechanism for loading MSW into a garbage truck during tipping of the container. A distinctive characteristic of the developed model is that it takes into account the wear of the friction pairs of the main elements of the hydraulic drive, which made it possible to describe the real conditions of its operation more accurately. Using numerical methods, the dynamic characteristics of the hydraulic drive at the start-up phase were studied, and the change in the main operating parameters of the system depending on the level of wear of its components was analyzed. The simulation results showed that taking into account the wear of friction pairs has a significant impact on the dynamics of the hydraulic drive for tipping the container during the loading of MSW into the garbage truck. In particular, significant changes in speed and power characteristics were found, as well as an increase in the time required to perform the technological operation. It was found that the duration of container tipping increases with the degree of wear of the hydraulic cylinder according to a power law, which indicates the nonlinear nature of the effect of wear on the efficiency of the mechanism. The obtained regularities can be used to predict the operating parameters of the hydraulic drive, establish maintenance intervals, and improve the reliability of MSW loading systems in garbage trucks.

The scientific work [30] is dedicated to the analytical study of an improved mathematical model of the hydraulic drive of the mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs. To perform design calculations for new garbage truck designs, it was obtained approximate analytical dependencies of pressure in the pressure line of the hydraulic cylinder, angular velocity, and container tipping angle as a function of time, based on the proposed linearized mathematical model of the hydraulic drive of the container tipping mechanism during the technological operation of MSW loading into a garbage truck during the first phase— rotation of the container to the equilibrium position, taking into account the wear of friction pairs. The obtained regression equation allows to approximately determine the duration of the first phase – the rotation of the container to the equilibrium position during its overturning in the technological operation of MSW loading into a garbage truck, taking into account the wear of friction pairs. This can be used during design calculations for new garbage truck designs, taking into account the wear of the executive bodies without the need to study the nonlinear mathematical model of the drive of its working bodies, as well as during the optimization of the main parameters of the hydraulic drive.

In the article [31], using a first-order experimental design with first-order interaction effects using the Box-Wilson method, an appropriate regularity of wear of the friction nodes of the garbage truck loading mechanism was determined based on the properties of anti-friction materials, and in the work [32], an appropriate regularity of maximum impact dynamic stresses in the most loaded section of the garbage truck manipulator boom is determined based on the wear of the manipulator hinge and its load level.

However, during the analysis of known publications, the authors did not find a complete methodology for the design calculation of the parameters of the mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs.

Aims of the article

Development of a scientifically grounded, improved methodology for the design calculation of the parameters of a mechanism for tipping a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs in order to determine its main geometric, force, and speed parameters.

Methods

The following methods were used in the work: analysis of scientific literature sources; synthesis of mathematical interdependencies of the main geometric, force, and speed parameters of the equipment; a systematic approach to take into account the interaction of all machine subsystems.

Results

Fig. 1 shows a schematic diagram of the hydraulic drive of the mechanism for container tipping in the technological operation of loading MSW into a garbage truck, taking into account the wear of friction pairs when using the rear MSW loading scheme.

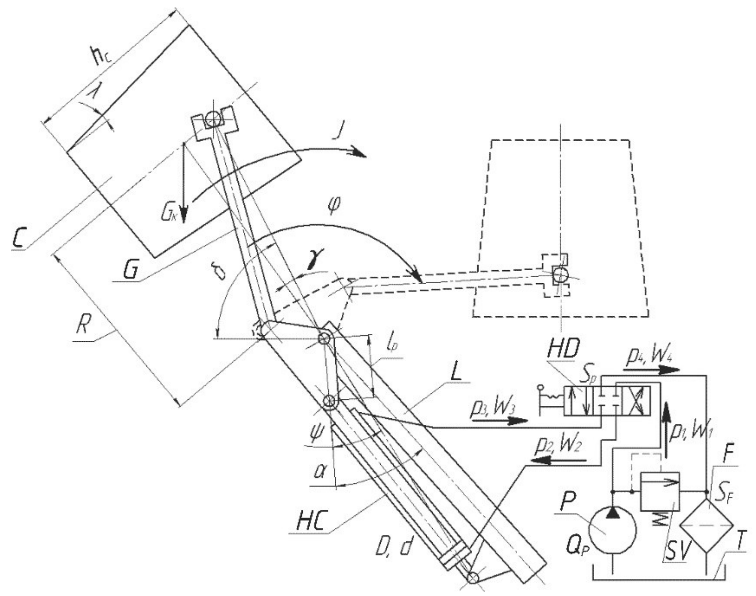

Fig. 1. Schematic diagram of the hydraulic drive of the container turning mechanism in the technological operation of MSW loading into a garbage truck, taking into account the wear of friction pairs

The diagram shows the following structural elements: C – container, G – gripper, L – lever, HC – hydraulic cylinder, HD – hydraulic distributor, P – hydraulic pump, SV – safety valve, F – filter, T – tank with working fluid, as well as the main geometric, kinematic and power parameters: p_1, p_2, p_3, p_4 – pressures at the pump outlet, at the hydraulic cylinder inlet, at the hydraulic cylinder outlet and at the filter inlet, respectively; W_1, W_2, W_3, W_4 – volumes of pipelines between the pump and the hydraulic distributor, the hydraulic distributor and the hydraulic cylinder inlet, the hydraulic cylinder outlet and the hydraulic distributor, the hydraulic distributor and the filter; Q_P –actual pump flow rate; S_P – cross-sectional area of the distributor opening; S_f – surface area of the filter element; D , d – piston and rod diameters; J – moment of inertia of moving elements; G_C –container weight; R – radius of rotation of moving elements; l_P – distance between the centers of rotation of the gripper and the rod; h – the height of the container; α – angle between the axes of the lever and the cylinder arm, γ – angle that takes into account the deviation of the center of mass position; δ – angle between the gripping arm and the horizontal; λ – angle of inclination of the container wall; ψ – the angle between the axis of the cylinder arm and the axis passing between the centers of rotation of the gripper and the hydraulic cylinder; φ – grip rotation angle.

The area of the rod cavity of the hydraulic cylinder of the container tipping mechanism can be found by using the following formula [30]:

$$S_{C1} = \frac{\pi\left(D^2 - d^2\right)}{4} \text{ [m}^2\text{]}. \tag{1}$$

The speed of the rods of the paired hydraulic cylinders of the container tipping mechanism can be determined by the formula [30]:

$$v = \frac{Q_P}{2S_{C1}} \text{ [m/s]}. \tag{2}$$

The pressure of the working fluid in the rod cavity of the hydraulic cylinder of the container tipping mechanism during steady-state operation can be found using the formula [30]:

$$p \approx \frac{GR\cos\left(\delta - \gamma\right)}{S_{C1} l_p \sin\left(\phi + \alpha\right)} \text{ [Pa]}. \tag{3}$$

The wear of friction components in the garbage truck loading mechanism due to the properties of anti-friction materials is determined according to the following regularity [31]:

$$u = 458.2f + 0.1696HB + 4366v - 546.2p + 33782fv \text{ [μm]}, \tag{4}$$

where u – wear of the manipulator joint, μm; f – coefficient of friction between steel and anti-friction material; HB – hardness of anti-friction material according to Brinell, MPa; v – sliding speed, m/s; p – pressure in the friction zone, MPa.

The maximum dynamic stress in the most loaded section of the manipulator boom due to wear of the manipulator hinge and its load level is found according to the following regularity [32]:

$$\sigma_{\max} = 0.08552u + 89.58\frac{G}{G_n} + 0.06243u\frac{G}{G_n} - 2.99 \cdot 10^{-5}u^2 - 10.02\left(\frac{G}{G_n}\right)^2 \text{ [MPa]}, \tag{5}$$

where σ_{max} – maximum dynamic impact stresses in the most loaded section of the manipulator boom, MPa; G/G_n – manipulator load rate; G – weight of a container with municipal solid waste, N; G_n – nominal load capacity of the manipulator, N.

Based on the obtained value of σ_{max} according to DSTU EN 1993-1-1:2010 [33], the grade of the manipulator boom material can be determined.

The average value of the container tipping angle for the first phase – the phase of turning the container to the equilibrium position can be determined by the formula [30]:

$$\overline{\varphi}_1 = \frac{\pi/2 + \lambda - \delta}{2} \text{ [rad]}. \tag{6}$$

The duration of container overturning, taking into account the wear of friction pairs during the first phase, is calculated using a simplified equation that is obtained in the article [30]:

$$t_1 \approx \frac{2S_{C1} l_p \beta_\sigma \sigma_0 J \sin\left(\overline{\phi}_1 + \psi\right)}{\left(Q_P - \alpha_\sigma\right)\left\{\beta_\sigma \sigma_0 J + 2S_{C1}^2 l_p^2 \sin^2\left[\overline{\phi}_1 + (\alpha + \psi)/2\right]\right\}} \phi_1 \text{ [s]}, \tag{7}$$

where σ_0 – coefficient of working fluid loss due to flow from a high-pressure area to a low-pressure area, without taking into account friction wear, $m^5/(N\cdot s)$; α_σ, β_σ – approximation coefficients of the dependence of working fluid losses on the duration of the friction pair wear process ($\alpha_\sigma = 4.054\cdot10^{-4}$; $\beta_\sigma = 128.1$).

The average value of the container tilt angle for the second phase—the phase of emptying MSW from the container into the garbage truck body can be determined by the following formula [34]:

$$\overline{\varphi}_2 = 0,75\pi + 1,5\lambda - \delta \text{ [rad]}. \tag{8}$$

The coefficient of working fluid loss due to flow from a high-pressure area to a low-pressure area, taking into account the wear of friction pairs, can be found using the formula [30]:

$$\sigma = \frac{\pi D\left(\delta_0 + u\cdot10^{-6}\right)^3}{12\nu\rho l} \text{ [m}^5\text{/(N·s)]}, \tag{9}$$

where δ_0 – nominal gap size, m; ν – kinematic viscosity of the working fluid, m^2/s; ρ – density of working fluid, kg/m^3; l – ring gap length, m.

The duration of container tipping during the second phase can be determined using a simplified equation that was obtained in [34]:

$$t_2 \approx \frac{2S_{C1}^2 l_p^2 \sin\left(\overline{\phi}_2+\alpha\right)\sin\left(\overline{\phi}_2+\psi\right)}{Q_P S_{C1} l_p \sin\left(\overline{\phi}_2+\alpha\right) - \sigma G R\cos\left(\delta-\gamma\right)}\phi_2 - \frac{2l_p}{Rg}\times$$
$$\times\sqrt{\frac{-Q_P S_{C1} l_p^2 \sin\left(\overline{\phi}_2+\alpha\right)\sin\left(\overline{\phi}_2+\psi\right)h_K\phi_2}{\sigma V_K \rho_B\left(1+2\tan\lambda\right)R^2 g^2\left[\cos\left(\delta-\lambda\right)+f_B\sin\left(\delta-\lambda\right)\right]\cos\left(\overline{\phi}_2+\delta-\gamma\right)}} \text{ [s]}. \tag{10}$$

The total duration of container tipping can be determined using the formula:

$$t = t_1 + t_2 \text{ [s]}. \tag{11}$$

The parameters of the mechanism for tipping the container with MSW into the garbage truck, taking into account the wear of friction pairs, calculated according to the proposed methodology, are given in the Table 1.

Table 1

Basic parameters of the mechanism for tipping a container with MSW into a garbage truck, taking into account the wear of friction pairs

S_{C1}, m²	v, m/s	p, MPa	u, μm	σ_{max}, MPa	material	$\overline{\varphi}_1$, rad	t_1, s	$\overline{\varphi}_2$, rad	σ, m⁵/(N·s)	t_2, s	t, s
$5.027\cdot10^{-3}$	0.0912	1.43	13.5	247	40Kh steel	0.271	0.755	1.378	$1.228\cdot10^{-10}$	4.196	4.95

The parameters of the mechanism for tipping the container with MSW into the garbage truck, taking into account the wear of the friction pairs, were obtained based on the following initial data: $D = 80$ mm; $d = 50$ mm; $Q_P = 55$ l/min; $G = 1742$ N; $R = 0.72$ m; $\gamma = 20°$; $\delta = 65°$; $l_p = 150$ mm; $\alpha = 40°$; $f = 0.1$; $HB = 250$ MPa; $G_n = 4900$ N; $\lambda = 6°$; $\alpha_\sigma = 4.054\cdot10^{-4}$; $\beta_\sigma = 128,1$; $\sigma_0 = 9.24\cdot10^{-11}$ $m^5/(N\cdot s)$; $J = 112.6$ $kg\cdot m^2$; $\psi = 30°$; $\delta_0 = 0.136$ mm; $\nu = 1.83\cdot10^{-5}$ m^2/s; $\rho = 890$ kg/m^3; $l = 35$ mm; $h_к = 0.46$ m; $V_k = 1.1$ m^3; $\rho_B = 210$ kg/m^3; $f_B = 0,3$.

The usage of the proposed improved method for engineering calculation of the parameters of the mechanism for tipping a container with MSW into a garbage truck, taking into account the wear of friction pairs, allows to significantly reduce the design time and avoid unreasonable costs for labor-intensive experimental and theoretical research.

The development of an improved method for project calculation of the parameters of the manipulation lever rotation mechanism during the loading of municipal solid waste into a garbage truck, taking into account the wear of friction pairs, requires further research.

Conclusions

A scientifically based improved algorithm for the design calculation of the parameters of the mechanism for turning a container with municipal solid waste into a garbage truck, taking into account the wear of friction pairs, is proposed, which allows to obtain its main geometric, force, and speed parameters. It has been established that the development of an improved methodology for the design calculation of the parameters of the manipulator lever rotation mechanism during the loading of municipal solid waste into a garbage truck, taking into account the wear of friction pairs, requires further research.

References

1. Holenko K., Dykha O., Koda E., Kernytskyy I., Horbay O., Royko Y., Fornalchyk Y., Berezovetska O., Rys V., Humenuyk R., Berezovetskyi S., Żółtowski M., Baryłka A., Markiewicz A., Wierzbicki T., Bayat H. (2024) Structure and strength optimization of the Bogdan ERCV27 electric garbage truck spatial frame under static loading. Applied Sciences, 14(23), 11012, https://doi.org/10.3390/app142311012

2. Dykha A., Sorokatyi R., Pasichnyk O., Yaroshenko P., Skrypnyk T. (2020, December) Machine wear calculation module in computer-aided design systems. In IOP Conference Series: Materials Science and Engineering, 1001(1), 012040, https://doi.org/10.1088/1757-899X/1001/1/012040

3. Kindrachuk M.V., Kharchenko V.V., Marchuk V.Y., Humeniuk I.A., Leusenko D.V. (2024) Methodology for Selecting Compatible Metal Materials for Friction Pairs During Fretting-Corrosion Wear. Metallophysics & Advanced Technologies, 46(7), 637-648, https://doi.org/10.15407/mfint.46.07.0637

4. Giel R., Dąbrowska A. (2021) Estimating time spent at the waste collection point by a garbage truck with a multiple regression model. Sustainability, 13(8), 4272, https://doi.org/10.3390/su13084272

5. Hao Y., Zhang Y., Ma N., Li P., Liu Y. (2024) Developing driving cycles for garbage trucks to estimate fuel consumption. Transportation Research Part D: Transport and Environment, 136, 104469, https://doi.org/10.1016/j.trd.2024.104469

6. Chulkov A.S., Chaplygin M.E., Shaykhov M.M. (2024) Justifying the Operation Parameters of a Robotic Cassette Loading Device of the Carousel Type for a Selection Seeder. Engineering Technologies and Systems, 34(4), 549-562, https://doi.org/10.15507/2658-4123.034.202404.549-562

7. Zhu B., Wang L., Wu J. (2022) Optimal design of loading device based on a redundantly actuated parallel manipulator. Mechanism and Machine Theory, 178, 105084, https://doi.org/10.1016/j.mechmachtheory.2022.105084

8. Guo J., Wang D., Li T., Gao S., Chen W., Fan R. (2018) Triaxial loading device for reliability tests of three-axis machine tools. Robotics and computer-integrated manufacturing, 49, 398-407, https://doi.org/10.1016/j.rcim.2017.05.009

9. Tinoco V., Silva M.F., Santos F.N., Morais R., Magalhães S.A., Oliveira P.M. (2025) A review of advanced controller methodologies for robotic manipulators. International Journal of Dynamics and Control, 13(1), 36, https://doi.org/10.1007/s40435-024-01533-1

10. Kuang X., Zhou S. (2024) Robotic Manipulator in Dynamic Environment with SAC Combing Attention Mechanism and LSTM. Electronics, 13(10), 1969, https://doi.org/10.3390/electronics13101969

11. Bronnikov A., Bendeberia M. (2024) Development of a manipulator kinematic model using ABB RobotStudio. Innovative Technologies and Scientific Solutions for Industries, 4(30), 5-18, https://doi.org/10.30837/2522-9818.2024.4.005

12. Calzada-Garcia A., Victores J.G., Naranjo-Campos F.J., Balaguer C. (2025) A Review on Inverse Kinematics, Control and Planning for Robotic Manipulators With and Without Obstacles via Deep Neural Networks. Algorithms, 18, 23, https://doi.org/10.3390/a18010023

13. Han R., Sang H., Liu F., Huang F. (2024) State of the Art and Development Trend of Laparoscopic Surgical Robot and Master Manipulator. International Journal of Medical Robotics and Computer Assisted Surgery, 20(6), e70020, https://doi.org/10.1002/rcs.70020

14. Polishchuk L.K., Piontkevych O.V., Svietlov A.V., Adler O.O., Lozinskyi D. (2025) Development and optimization of the control devicefor the hydraulic drive of the belt conveyor. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, 15, 124-129, http://doi.org/10.35784/iapgos.7051

15. Petrov O., Kozlov L., Lozinskiy D., Piontkevych O. (2019) Improvement of the hydraulic units design based on CFD modeling. Lecture Notes in Mechanical Engineering, 653-660, https://doi.org/10.1007/978-3-030-22365-6_65

16. The Cabinet of Ministers of Ukraine (2004) Resolution No. 265 "Pro zatverdzhennia Prohramy povodzhennia z tverdymy pobutovymyvidkhodamy" ["On Approval of the Program for Solid Waste Management"]. URL: http://zakon1.rada.gov.ua/laws/show/265-2004-%D0%BF.

17. Lazea M., Constantin G.A., Stoica D., Voicu G. (2020) Analiza structurala cu elemente finite a pieselor de uzura de pe placa de contrapresiune a unei autogunoiere. Revista Romana de Materiale, 50(2), 283-293.

18. Qiu Z., Min R., Wang D., Fan S. (2022) Energy features fusion based hydraulic cylinder seal wear and internal leakage fault diagnosis method. Measurement, 195, 111042, https://doi.org/10.1016/j.measurement.2022.111042

19. Li H., Li Y. (2025) Finite element analysis and structural optimization design of multifunctional robotic arm for garbage truck. Frontiers in Mechanical Engineering, 11, 1543967, https://doi.org/10.3389/fmech.2025.1543967

20. Chernik D.V., Chernik K.N. (2020) Mathematical model of a combined manipulator of a forest machine. In IOP Conference Series: Materials Science and Engineering, 5(919), 052037,

https://doi.org/10.1088/1757-899X/919/5/052037

21. Kot T., Bobovský Z., Vysocký A., Krys V., Šafařík J., Ružarovský R. (2021) Method for robot manipulator joint wear reduction by finding the optimal robot placement in a robotic cell. Applied Sciences, 11(12), 5398, https://doi.org/10.3390/app11125398

22. Serebryanskii A. (2014) Except the negative reverse effect and automatically compensate for wear in the hinge manipulators. DOAJ – Lund University: Concept: Scientific and Methodological e-magazine, 4 (Collected works, Best Article).

23. Zadorozhnaya E., Levanov I., Kandeva M. (2018, May) Tribological research of biodegradable lubricants for friction units of machines and mechanisms: Current state of research. In International Conference on Industrial Engineering, 939-947, https://doi.org/10.1007/978-3-319-95630-5_98

24. Beisembayev A., Yerbossynova A., Pavlenko P., Baibatshayev M. (2023) Planning trajectories of a manipulation robot with a spherical coordinate system for removing oxide film in the production of commercial lead, zinc. Eastern-European Journal of Enterprise Technologies, 124(2), 80, https://doi.org/10.15587/1729-4061.2023.286463

25. Kargin R.V., Yakovlev I.A., Shemshura E.A. (2017) Modeling of workflow in the grip-container-grip system of body garbage trucks. Procedia Engineering, 206, 1535-1539, https://doi.org/10.1016/j.proeng.2017.10.727

19. Skyba M.Ye., Misiats O.V., Polishchuk A.O., Misiats V.P., Rubanka M.M. (2021). Systema adaptyvnoho chastotnoho keruvannia shvydkistiu obertannia asynkhronnoho tryfaznoho elektrodvyhuna pryvodu rotornoi drobarky [Adaptive frequency control system for the rotational speed of a three-phase asynchronous electric motor driving a rotary crusher]. Herald of of Khmelnytskyi National University. Technical Sciences, 2(295), 139-146, https://doi.org/10.31891/2307-5732-2021-295-2-139-146

27. Manoilenko O., Dvorzhak V., Horobets V., Panasiuk I., Bezuhlyi D. (2024) Assessing the impact of sewing machine thread take-up mechanism parameters on the magnitude and nature of thread take-up. Eastern European Journal of Enterprise Technologies, 2024, 6(1(132)), 64-75, https://doi.org/10.15587/1729-4061.2024.315129

28. Iskovich-Lototsky R., Kots I., Ivanchuk Y., Ivashko Y., Gromaszek K., Mussabekova A., Kalimoldayev M. (2019). Terms of the stability for the control valve of the hydraulic impulse drive of vibrating and vibro-impact machines. Przeglad Elektrotechniczny, 4(19), 19-23, https://doi.org/10.15199/48.2019.04.04

29. Bereziuk O.V., Yavorskyi V.Ye. (2025) Udoskonalena matematychna model roboty hidropryvodu mekhanizmu zavantazhennia tverdykh pobutovykh vidkhodiv u smittievoz iz urakhuvanniam znosu par tertia [Improved mathematical model of the hydraulic drive of the mechanism for loading solid household waste into a garbage truck, taking into account friction pair wear]. Scientific Works of Vinnytsia National Technical University, 1, 154-164, https://doi.org/10.31649/2307-5376-2025-1-154-164

30. Bereziuk O.V., Savulyak V.I., Kharzhevskyi V.O., Ivanov S.Cv., Yavorskyi V.Ye. (2025) Analytical study of a hydraulic drive model for a municipal waste container overturning mechanism in a garbage truck considering the wear of friction pairs. Problems of Tribology, 30(3/117), 30-49, https://doi.org/10.31891/2079-1372-2025-117-3-30-40

31. Bereziuk O.V., Savulyak V.I., Kharzhevskyi V.O., Serdiuk O.V., Yavorskyi V.Ye. (2024) Dependence of wear of friction pairs of the mechanism for loading solid household waste into a garbage truck on the characteristics of antifriction materials. Problems of Tribology, 29(3/113), 24-30, https://doi.org/10.31891/2079-1372-2024-113-3-15-23

32. Bereziuk O.V., Savulyak V.I., Kharzhevskyi V.O., Yavorskyi V.Ye. (2023) The influence of hingeswear on the dynamic load of the articulated boom of a garbage truck's manipulator. Problems of Tribology, 28(3/109), 18-24, https://doi.org/10.31891/2079-1372-2023-109-3-18-24

33. State Enterprise "Ukrainian Scientific and Research Center for Standardization, Certification and Quality" (UkrNDNC). (2010) DSTU EN 1993-1-1:2010. Eurocode 3. Design of steel structures. Part 1-1: General rules and rules for buildings. Kyiv: UkrNDNC.

34. Bereziuk O.V. (2021) Naukovo-tekhnichni osnovy proektuvannia pryvodiv robochykh orhaniv mashyn dlia zbyrannia ta pervynnoi pererobky tverdykh pobutovykh vidkhodiv [Scientific and technical grounds for designing drives for working bodies of machines for collecting and primary processing of municipal solid waste]. Doctor of Engineering Sciences Dissertation (Specialty 05.02.02 – Machine Science). Khmelnytskyi, 482 p.

Березюк О.В., Савуляк В.І., Харжевський В.О., S.Cv. Ivanov, Яворський В.Є. Удосконалений алгоритм інженерних розрахунків параметрів механізму перевертання контейнера у сміттєвоз із урахуванням зносу пар тертя

Стаття присвячена розробці на основі аналізу наукових літературних джерел науково-обґрунтованої удосконаленої методики проєктного розрахунку параметрів механізму перевертання контейнера з твердими побутовими відходами у сміттєвоз із урахуванням зносу пар тертя з метою визначення основних його геометричних, силових та швидкісних параметрів. Привод робочих органів механізму перевертання контейнера з твердими побутовими відходами у сміттєвоз – гідравлічний з джерелом живлення від насосної станції сміттєвоза. Використання запропонованої удосконаленої методики інженерного розрахунку параметрів механізму перевертання контейнера з твердими побутовими відходами у сміттєвоз із урахуванням зносу пар тертя дозволяє суттєво скоротити час проєктування, уникнути необґрунтованих витрат на трудомісткі експериментальні та теоретичні дослідження. За допомогою запропонованої науково-обґрунтованої удосконаленої методики проєктного розрахунку параметрів механізму перевертання контейнера з твердими побутовими відходами у сміттєвоз із урахуванням зносу пар тертя визначено основні його геометричні, силові та швидкісні параметри. Встановлено, що розробка удосконаленої методики проєктного розрахунку параметрів механізму повороту важеля маніпулятора під час завантаження твердих побутових відходів у сміттєвоз із урахуванням зносу пар тертя вимагає проведення подальших досліджень.

Ключові слова: алгоритм, методика проєктного розрахунку, урахування зносу, гідропривод, знос, вузли тертя, механізм перевертання контейнера, сміттєвоз, тверді побутові відходи.