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МОДЕЛЮВАННЯ НАПІВПРИЧІПНОГО СКРЕПЕРА З УСІМА ПРОВІДНИМИ КОЛЕСАМИ

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Анотація. Постановка проблеми. Проектування сучасних землерийно-транспортних машин потребує створення та використання розрахункових схем та математичних моделей, які дозволяють розглянути питання навантаження вузлів металоконструкції. Аналіз роботи самохідних та напівпричіпних пневмоколісних скреперів дозволяє зробити висновок про недостатність зчіпних якостей для повного заповнення ковша грунтом. З метою підвищення тягових властивостей зараз широко використовуються потужні повноприводні тягачі, з якими агрегатується скреперне обладнання з провідними задніми колесами, що потребує визначення та дослідження зусиль, діючих в основних елементах конструкції. ***Мета.*** Визначення закономірностей навантаження металоконструкції напівпричіпного скрепера з усіма провідними колесами та раціонального розподілу тягових зусиль між тягачем і скрепером на основі розробленої розрахункової схеми та математичної моделі. ***Висновок.*** Наведено результати моделювання напівпричіпного скрепера з усіма провідними колесами, які дозволили визначити режими роботи, що забезпечують зниження навантаженості металоконструкції тягової рами.

Ключові слова: скрепер; моделювання; робочий процес; навантаження; металоконструкція; провідні колеса.

МОДЕЛИРОВАНИЕ ПОЛУПРИЦЕПНОГО СКРЕПЕРА СО ВСЕМИ ВЕДУЩИМИ КОЛЕСАМИ

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Аннотация. Постановка проблемы. Проектирование современных землеройно-транспортных машин требует создания и использования расчетных схем и математических моделей, позволяющих рассмотреть вопросы нагрузки узлов металлоконструкции. Анализ работы самоходных и полуприцепных пневмоколесных скреперов позволяет сделать вывод о недостаточности сцепных качеств для полного заполнения ковша грунтом. С целью повышения тяговых свойств широко используются мощные полноприводные тягачи, с которыми агрегатируется скреперное оборудование с ведущими задними колесами, что требует определения и исследования усилий, действующих в основных элементах конструкции. ***Цель***. Определение закономерностей нагружения металлоконструкции полуприцепного скрепера со всеми ведущими колесами и рационального распределения тяговых усилий между тягачом и скрепером на основе разработанной расчетной схемы и математической модели. ***Вывод.*** Приведены результаты моделирования полуприцепного скрепера со всеми ведущими колесами, которые позволили определить режимы работы, обеспечивающие снижение нагруженности металлоконструкции тяговой рамы.

Ключевые слова: скрепер; моделирование; рабочий процесс; нагружение; металлоконструкция; ведущие колеса.

SIMULATION OF A SEMITRAILER SCRAPER WITH ALL DRIVING WHEELS

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Abstract. Problem statement. The design of modern earth-moving machines requires creating and using design schemes and mathematical models that allow to consider the problems of steel structures loading. The analysis of the operation of self-propelled and semi-trailed pneumatic wheel scrapers allows to make a conclusion of their insufficient traction property to completely fill the bucket with soil. In order to increase traction properties, powerful all-wheel drive tractors are widely used, with which the scraper equipment with leading rear wheels is aggregated, that requires the definition and study of the forces acting in the main structural elements. ***The purpose of the paper.*** Determining the regularities of loading the steel structure of the semi-trailer scraper with all driving wheels and the rational distribution of traction forces between the tractor and the scraper on the basis of the developed design scheme and the mathematical model. ***Conclusion***. The results of the simulation of a semi-trailer scraper with all driving wheels are presented, which allow to determine the operation modes that provide the reduction of the load on the steel structure of the traction frame.

Keywords: scraper; modeling; working process; loading; steel structure; driving wheels.

Problem statement. Scrapers are often used in earthwork in road and forestry construction, as well as in coal mining and extractive industries. The analysis of work of self-propelled and semi-trailer pneumatic wheel scrapers allows to make a conclusion of insufficient traction properties of the machines for the complete filling of the bucket with soil, which results in decreasing the efficiency of the planned work [1, 2].

Among numerous means of increasing the scraper efficiency, one of the most common is the use of four-wheel drive machines [3], in which the torque to the rear axle is transmitted from the main or the secondary engine, which increases the degree of filling the bucket, reduces the path and time of digging, but leads to changing loads acting in the units of the scraper steel structure.

Thus, there is an urgent need to improve the efficiency of operation of pneumatic scrapers with all the leading wheels due to the use of rational operating modes and determination of the regularities of loading the scraper steel structure based on the developed design scheme and mathematical model.

The analysis of publications. Investigation of the traction-coupling capacity of a semi-trailer scraper due to the installation of a leading rear axle [4] proved the possibility of a significant increase in efficiency, though the problem of loading the steel structure was not considered.

The mathematical and computer simulation of a semi-trailer scraper working as a part of the train [5, 6], allowed to determine the rational modes of operation and regularities of loading the main units of the steel structure, but the received results cannot be fully applied to the all-wheel drive scraper.

The problem of determining the forces that act in the drawbar of a self-propelled scraper with all driving wheels based on the developed mathematical model is considered in [7], but the effect of distribution of the traction force between the tractor and the scraper on the load was not studied. The work of the scraper with soils of different categories that affect the character of the processes also was not considered, thus, the model needs to be improved.

The research is well known [8, 9], in which loading the scraper steel structure is considered on the basis of statically operating forces, without taking into account the dynamic component, that causes errors in research and calculations.

Experimental studies of loading the models of the rear walls of the scraper bucket in the conditions of changing the height of the fixation of the hydraulic cylinder actuator with the use of the polarization-optical method and comparison with the calculations by finite element methods showed that the traditional design of the rear wall of the scraper requires improvement in terms of optimal configuration and strength [10]. In the future the proposed method can be used to study the loading of the drawbar.

Mathematical modeling of a semi-trailer scraper with all driving wheels. The analysis of the design and operating conditions of the scrapers allowed to determine the reasonable constraints, as well as to simplify the development of the design and mathematical models and the conducting of the research [10, 11].

As assumptions, it was accepted to consider the plane problem without longitudinal and transverse slopes.

In the dynamics of the process of digging the soil by a scraper, it is known that the drawbar is an elastic element whose rigidity is much lower than that of the other units of the steel structure of the machine; the rigidity of the scraper in the vertical direction is determined by the elasticity of the drawbar and the pneumatic wheels.

The bearing surface is rigid without a possibility of deformation, the longitudinal forces on the driving wheels are limited by the coupling properties of the propulsion units with the bearing surface, and the pneumatic tires have vertical elasticity and viscous properties. The tractor and the scraper are considered as absolutely rigid bodies that have concentrated masses applied in coordinates of the centers of gravity.

In accordance with the taken assumptions, the design model of a semi-trailer scraper for digging the soil (Fig. 1) is presented by a two mass system m_1, m_2 that performs longitudinal, vertical and angular displacements x, y, φ, which takes into account the tractive forces on the driving wheels of the tractor T_1, T_2 and the scraper T_3, the reaction of the soil on the axles R_1, R_2, R_3, resistance to rolling the wheels F_1, F_2, F_3, horizontal and vertical components of the resistance to digging, applied to the scraper knife R_G, R_B, gravity G_1, G_2.

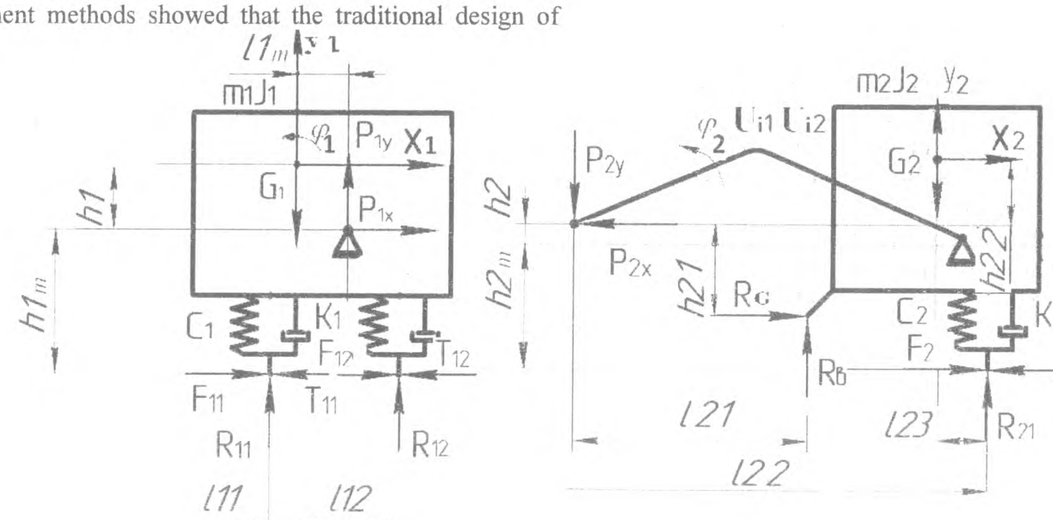

Fig. 1. The design model of a semi-trailer scraper

Elastic links of the system are characterized by the coefficients of rigidity of the scraper drawbar in the horizontal and vertical plane U_1, U_2, radial rigidity of the driving wheels of the tractor C_1, C_2 and scraper C_3, with a viscous resistance K_1, K_2, K_3.

To establish equations of motion of a semi-trailer scraper with respect to generalized coordinates, speeds of the weight centers of a tractor and a scraper were determined, as well as kinetic energies and their derivatives from speed and time, generalized forces, that act from driving wheels and a drawbar.

The forces acting on the tractor and scraper from the front and rear driving wheels are equal to:

$$R_1 = C_1[-y_1 + (l_1 + l_{1m})\varphi_1] + k_1[-\dot{y}_1 + (l_1 + l_{1m})\dot{\varphi}_1]; \quad (1)$$

$$R_2 = C_1[-y_1 - (l_2 - l_{1m})\varphi_1 + k_1[-\dot{y}_1 - (l_2 - l_{1m})\dot{\varphi}_1]; \quad (2)$$

$$R_3 = C_2(-y_2 + l_{22}\varphi_2) + k_2(-\dot{y}_2 - l_{22}\varphi_2). \quad (3)$$

The forces acting on the tractor and scraper from the drawbar are equal to:

$$P_{ix} = U_{11}\Delta x_i + U_{12}\Delta y_i; \quad (4)$$

$$P_{iy} = U_{21}\Delta x_i + U_{22}\Delta y_i. \quad (5)$$

where Δx_i is the extension of the drawbar in the horizontal direction, Δy_i is the extension of the drawbar in the vertical direction.

The values $\Delta x_i, \Delta y_i$ are defined as the difference in the movement of attachment points of the drawbar to the tractor and scraper:

$$\Delta x_1 = x_1 - x_2; \quad (6)$$

$$\Delta y_1 = y_1 - y_2. \quad (7)$$

The coefficients U_1, U_2 are calculated according to the deformations of the drawbar with the use of the finite element method. For this, in addition to the forces that act from the tractor to the scraper, only the horizontal forces of a certain value were applied, and then only the vertical forces [6].

The forces of resistance to cutting the soil were determined by the intensity of the growth of resistance to digging:

$$\begin{aligned} R_G &= Ax_2; \\ R_B &= R_G\psi, \end{aligned} \quad (8)$$

where A is the intensity of growth of resistance to digging, which is determined by the type and category of soil.

The value of the traction effort is determined by the coupling weight of the machine and the coefficient of engagement φ:

$$\begin{aligned} T &= T_1 + T_2 + T_3; \\ T &= (G_1 + G_2 - R_B)\varphi. \end{aligned} \quad (9)$$

The mathematical model of a semi-trailer scraper, taking into account the assumptions made, will take the form:

$$\begin{aligned}
& m_1 \cdot \ddot{x}_1 + m_1 h_1 \ddot{\varphi}_1 = T_{11} + T_{12} - F_{11} - F_{12} - U_{11}(x_1 - x_2) - \\
& -U_{12}(y_1 - y_2); \\
& m_1 \cdot \ddot{y}_1 + m_1 l_{1m} \ddot{\varphi}_1 = -C_1 y_1 + C_1[(l_{11} + l_{1m}) - (l_{12} - l_{1m})]\varphi_1 - \\
& -k_1 \dot{y}_1 + k_1[(l_{11} + l_{1m}) - (l_{12} - l_{1m})]\dot{\varphi}_1 + U_{21}(x_1 - x_2) + \\
& +U_{22}(y_1 - y_2); \\
& m_1 h_1 \ddot{x}_1 + m_1 l_{11} \ddot{y} + \left[m_1\left(h_1^2 + l_{1m}^2\right) + J_1\right]\ddot{\varphi}_1 = -C_1(l_{11} + l_{1m})y_1 + \\
& +C_1(l_{11} + l_{1m})^2\varphi_1 - k_1(l_{11} + l_{1m})\dot{y}_1 + k_1(l_{11} + l_{1m})^2\dot{\varphi}_1 - \\
& -C_1(l_{12} + l_{1m})y_1 + C_1(l_{12} + l_{1m})^2\varphi_1 - k_1(l_{12} + l_{1m})\dot{y}_1 + \\
& +k_1(l_{12} + l_{1m})^2\dot{\varphi}_1 + F_{11}h_{1m} + F_{12}h_{1m} - T_{11}h_{1m} - T_{12}h_{1m}. \\
& m_2 \cdot \ddot{x}_2 + m_2 h_2 \ddot{\varphi}_2 = T_2 - R_G - F_{21} + U_{11}(x_1 - x_2) + \\
& +U_{12}(y_1 - y_2); \\
& m_2 \cdot \ddot{y}_2 + m_2(l_{22} - l_{23})\ddot{\varphi}_2 = -C_2 y_2 + C_2 l_{22}\varphi_2 - k_2 \dot{y}_2 + \\
& +k_2 l_{22}\dot{\varphi}_2 - U_{21}(x_2 - x_1) - U_{22}(y_2 - y_1) + R_B, \\
& m_2 h_2 \ddot{x}_2 + m_2(l_{22} - l_{23})\ddot{y}_2 + \left[m_2\left(h_2^2 + l_{2m}^2\right) + J_2\right]\ddot{\varphi}_2 = \\
& = C_C(x_3 - x_2)h_2 + C_2 l_{22} y_2 + C_2 l_{22}{}^2\varphi_2 + \\
& +k_2 l_{22}\dot{y}_1 - k_2 l_{22}{}^2\dot{\varphi}_2 + F_{21}h_{2m} + R_G h_{21} + R_B l_{21}.
\end{aligned} \quad (10)$$

When modeling load modes, boundary conditions were used which took into account a number of limitations on the action of forces resisting to digging and moving as well as reactions of the soil on the wheels.

The elastic force is revealed only when compressing pneumatic tires:

$$R_i = \begin{Bmatrix} c_i y_i & y_i > 0 \\ 0 & y_i \le 0 \end{Bmatrix}. \quad (11)$$

The force of resistance to motion acts at $R_i > 0$:

$$F_i = \begin{Bmatrix} R_i f & R_i > 0 \\ 0 & R_i \le 0 \end{Bmatrix}. \quad (12)$$

The horizontal and vertical forces of resistance to cutting the soil are the following:

$$\begin{aligned} R_G &= \begin{Bmatrix} R_G & \dot{x} > 0 \\ 0 & \dot{x} \le 0 \end{Bmatrix}; \\ R_B &= \psi R_G. \end{aligned} \quad (13)$$

When modeling the load of a steel structure, there was a change in the ratio of the traction effort, which is realized by the tractor and the scraper in the range from: $T_1 = 100\%$ when the drive of the rear axle is switched off, to the values: $T_1 = 30\%$, $T_2 = 70\%$ of the total tractive effort.

The analysis of the results of calculations with the use of the created mathematical model showed that the dynamics of processes that arise in the horizontal plane, to a large extent exceed the others.

Changes in loading have a similar vibration character and reach maximum values during the first half-period (Fig. 2).

The greatest efforts arise in the operation of a scraper with the front drive, they have a rapid rate of growth with the dynamic factor equal to 1.9.

When connecting the rear drive, the rate and magnitude of the emerging loads are reduced, and the dynamic factor is equal to 1.1–1.5 when the rear axle of the scraper realizes 30 and 50% of the total traction power respectively.

When transmitting 70% of the total traction to the rear axle, the character of vibration processes changes somewhat, namely: the amplitude increases while the rate of growth and the maximal values are practically not changeable.

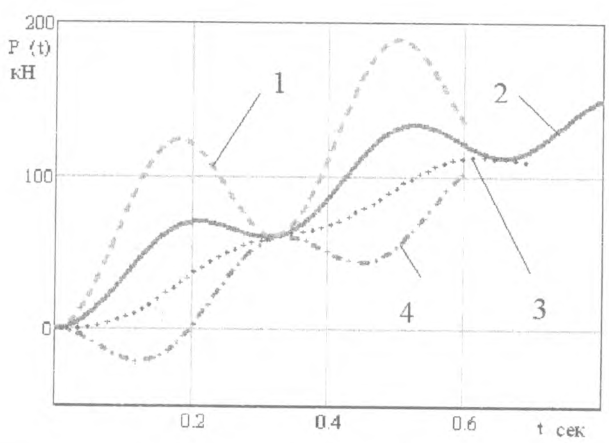

Fig. 2. Results of simulation of traction load processes: 1 – scraper with front drive, $T_1 = 100\%$, 2-4 – scraper with full drive, $T_1 = 70\%$, 50%, 30% of the total traction power respectively

Thus, the operation of a semi-trailer full-drive scraper leads to a reduction in the load of the drawbar, and the option of an even distribution of the traction effort between the tractor and the scraper should be recognized as the most acceptable mode.

In order to determine the impact of the category and type of soil being excavated, on the amount of effort in the drawbar, the research of the load dependence on the ratio of the traction power of the scraper T_2 and the tractor T_1 and the intensity of the growth of the resistance to digging A was carried out, the results of which are given in Fig. 3

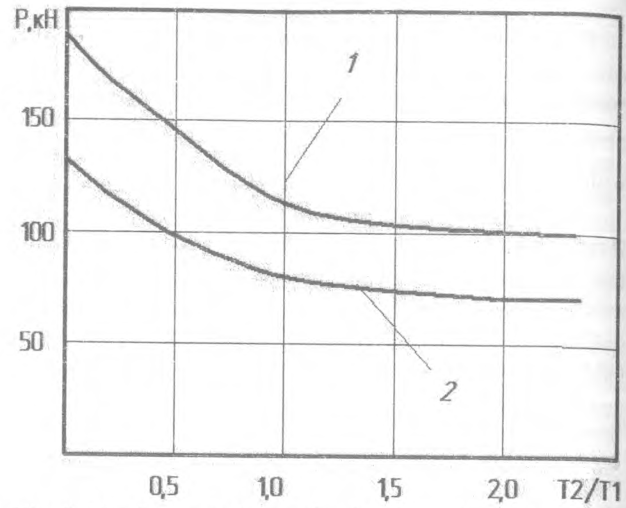

Fig. 3. The forces acting in the drawbar of the scraper: 1 - $A = 250$ kN, 2 - $A = 100$ kN

As an indicator characterizing the soil, the intensity of the growth of resistance to digging A is taken, which for the main types of soils being excavated by the scraper, varies in the range from 100 to 250 kN/ \m.

The results of the research have shown that with the decrease of the category of soils, the forces acting in the drawbar decrease proportionally.

The character of the curves confirms the conclusions made when analyzing the processes of loading, that the even distribution of traction efforts between the tractor and the scraper is the most rational mode.

This assertion is proved by the fact of the limited technical feasibility to achieve a more substantial redistribution of traction between the front and rear wheels.

Conclusions. The design model of a semi-trailer scraper with all driving wheels was developed, on the basis of which, taking into account the grounded restrictions and boundary conditions, a two-mass mathematical model with the possibility of movement in three directions was created.

As a result of the simulation it was established that the longitudinal deformations of the steel structure considerably exceed the vertical ones.

The loading processes have the same character, and the forces in the drawbar of the scraper with the leading front wheels are 21–46% higher than those in the machine with all the driving wheels.

The mode of operation in which the traction force is evenly distributed between the tractor and the scraper that gives the lowest acting forces with the dynamic factor of 1.2, should be considered the most rational one.

The obtained results can be used for soils of different categories, which are characterized by an increase in the resistance to digging from 100 to 250 kN/m.

Thus, the use of semi-trailer scrapers with all driving wheels can significantly reduce the load of the drawbar and increase the efficiency of work.

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