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STUDY OF THE INTERACTION OF A SHORT-BASE LOADER WITH A SUPPORTING SURFACE DURING TRANSPORT OPERATIONS

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Abstract. *The relevance of the work lies in the creation and improvement of loading and unloading machines. This article deals with the transport mode of a short-base loader PMTS 1200, namely, the process of moving over a single obstacle. Due to the short base and the centre of gravity, which is structurally located closer to the rear axle, when overcoming unevenness of the working surface, the machine loses stability as a result of the rear wheels detaching from the bearing surface, which reduces its efficiency and productivity. Therefore, there is a need to increase the efficiency of short wheel loaders when overcoming unevenness on the work site by using an intelligent control system in transport mode, which increases the stability of the machine. On the other hand, machine control automation systems require consideration of the transport mode, mathematical modelling of the machine, and algorithmisation of workflows, as these parameters are essential for the development of control systems. Thus, the creation of adaptive systems for automatic control of short wheel loaders' work processes is an urgent scientific and technical problem, the solution of which is of great economic importance for the construction industry. Using the developed mathematical models, the dependencies characterising the interaction of the forklift wheels with the bearing surface were obtained, which are complex in nature, but they reflect the interaction of a short wheel loader with an obstacle and can be used to assess the stability of the machine and the traction capabilities of its individual wheels.*

Keywords: *short wheel loader; unevenness; stability; working surface; transport mode.*

Introduction

The ever-increasing volume of work in construction necessitates the production of small-sized multi-purpose machines alongside medium and heavy-duty machines, which can significantly reduce the share of manual labour. Short-base loaders with a hydraulic transmission are the most common in terms of the number of models produced (more than 140). They have a wide range of interchangeable working bodies (more than 70 items). Due to their versatility, efficiency, high mobility and manoeuvrability, as well as ease of operation combined with quick change of working bodies, short wheel loaders are a highly efficient means of mechanising manual labour at small and scattered construction sites where the use of heavier machines is impractical or impossible. Currently, more than 25 companies in the US, UK, Germany, Japan, Canada, Italy, Slovakia and China manufacture short wheel loaders for both the domestic and foreign markets, with an annual output of about 100,000 machines (80% in the US, where construction uses about 30% of these machines) [1].

This type of forklift is a versatile vehicle designed for unloading operations and other work at the work site. Thanks to its well-thought-out design, the forklift is able to operate in confined spaces, which makes this type of transport indispensable in such situations.

The layout of short wheel loaders is determined by the small size of the machine and the need to ensure stability against tipping over. A striking example of a successful and rational layout is the small-sized skid steer loader, which consists of an engine, frame, hydraulic transmission, on-board gear, chassis, and hydraulically driven working equipment. Such machines have a monoblock welded frame formed by two box spars, which are also connected by box transverse links. Small-sized skid steer loaders have a fairly rigid wheel suspension and a frame that is used not only as a strong frame for the machine body, but also as a container for hydraulic fluid.

Modern short wheel loaders are equipped with either a torque converter or a hydromechanical transmission. Small-sized forklifts with a torque converter have lower fuel consumption and higher performance compared to hydromechanical forklifts. Forklifts equipped with a torque converter have the following advantages:

- infinitely variable speed control over a wide range;
- side steer machines have an independent drive for each side;
- protection of the motor against overload;
- ease of repair and maintenance;

- the ability to freely arrange and assemble units and equipment from serially produced elements.

Despite the advantages of these machines due to their manoeuvrability and a wide range of quick-change attachments, they have a number of disadvantages. For example, these machines with standard tyres can slip on loose soils, get stuck in sand or soil, and do not provide a "comfortable ride" on uneven surfaces. However, the transport mode is not without its drawbacks, as due to the short base and the centre of gravity, which is structurally located closer to the rear axle, the machine loses stability when overcoming unevenness in the working area, which reduces its efficiency and productivity [2].

Due to the relatively short period of time that has passed since the creation of short-base loaders and the insufficient amount of research, there are still no methods and recommendations for the design and operation of machines of this type. It should also be noted that the forklifts produced in Ukraine are mainly created by copying similar machines of foreign companies, and therefore do not surpass them in terms of technical indicators, but due to their low cost, they are most widely used in Ukraine. It should be noted that foreign forklifts usually have a higher lifting capacity than short-base domestic forklifts (the lifting capacity of foreign machines is 10% higher than that of domestic counterparts). This is due to the safety devices that foreign forklifts of this type are equipped with (Bobcat, Caterpillar, Mustang, Komatsu, etc.). The lack of use of advanced technologies compared to foreign analogues has led to lower productivity and an increase in the overall weight of the machine.

Analysis of the latest research and publications

One of the indicators of machine operation safety is their stability during work operations and in the transport mode. Analysis of the designs of short-base loaders with adjustable hydraulic transmissions and exploratory experiments show that their stability must be ensured not only in the positions stipulated by the standards, but also in the transport mode of movement with the occurrence of a possible emergency, for example, when the machine overcomes a single bump. From this perspective, let's look at the main works on assessing the stability of forklifts and the most similar to them in terms of technological processes of other machines [3]. The acceptance rules and test method for front wheel loaders provide for the determination of their static stability in two cases:

- on a horizontal surface with the highest permissible load at the maximum bucket outreach. The safety factor, which is the ratio of the holding to the overturning moment relative to the front supports, should be greater than 2.0. The same is noted in the works of leading experts in the design and operation of forklifts A. V. Bazanov, G. B. Zabegalov, L. A. Hoberman, V. M. Kazarinov, and others. The latter three papers show that forklifts of traditional design lose stability even with a slight detachment of the rear wheels. In view of this, it should be noted that for short-base forklifts, it is quite acceptable for the running wheels to detach from the bearing surface;

-on forward and backward sloping support surfaces with and without the largest load in the bucket, respectively. The permissible angles of inclination of the support surface must exceed 20°, i.e. this is how the regulations provide for the assessment of longitudinal stability.

In all of the above cases, the forklift is stationary during the test, and no inertial forces are assumed.

In the textbook by Professors A. M. Kholodov, V. V. Nichke, and L. V. Nazarov, the stability of loaders and earthmoving and transport machines in motion is assessed taking into account the action of inertial forces. In one of the cases, the longitudinal stability of a machine (for example, a bulldozer) is considered during its braking [4]. The study determined the maximum angle of inclination of the bearing surface with a safety factor of at least 1.2. The authors studied a bulldozer or wheeled loader moving at transport speed on a rounded road section and subject to centrifugal forces. The dynamics of lifting machines was also modelled by V. S. Loveikin and I. O. Nefyodov, whose work suggests ways to reduce dynamic loads on the front loader's loader.

The inertial forces arising from the braking of a lowering forklift boom were taken into account in the works of V. M. Veksler and T. I. Mukha. To this end, they took into account the pliability of the running wheels and the bearing surface. However, in this study, only a flat scheme of force action on a stationary forklift was considered.

Due to the design features of small wheeled loaders, the issue of longitudinal stability is particularly important when the machine is operating in transport mode with loaded working equipment.

Presentation of the main material

The movement of a short wheel loader over rough terrain is characterised by many specific features. The interaction of individual wheels with single bumps, the size of which can be up to 0.18 of the radius of the running wheels, manifests itself in uneven spatial loading of the machine's chassis. A sharp change in vertical reactions (from zero to a maximum of several times the nominal value) on individual wheels leads to sharp oscillations of the machine, and due to the design features of this class of machines, this causes the rear wheels to hang out when driving over an obstacle and, as a result, loss of longitudinal stability.

The need to take these and other factors into account when assessing the stability of machines of this class requires preliminary mathematical modelling of the forklift movement process with simulation of traffic conditions close to the real one.

The mathematical model presented in this section was developed for a two-axle short-base forklift [5]. We consider the overcoming of a single boundary obstacle, the height of which is compared to half the radius of the forklift wheel (Fig. 1).

The following assumptions were made in developing the mathematical model:

- The paper considers the movement of a forklift in the longitudinal vertical plane without taking into account the forces acting in the lateral direction and assuming that both wheels of one axle come into contact with an obstacle simultaneously (a flat design scheme for the movement of a short wheelbase forklift is assumed);
- The elastic characteristics of the tyres are assumed to be linear and the same for all wheels;
- the stiffness on the obstacle edge is assumed to be constant.

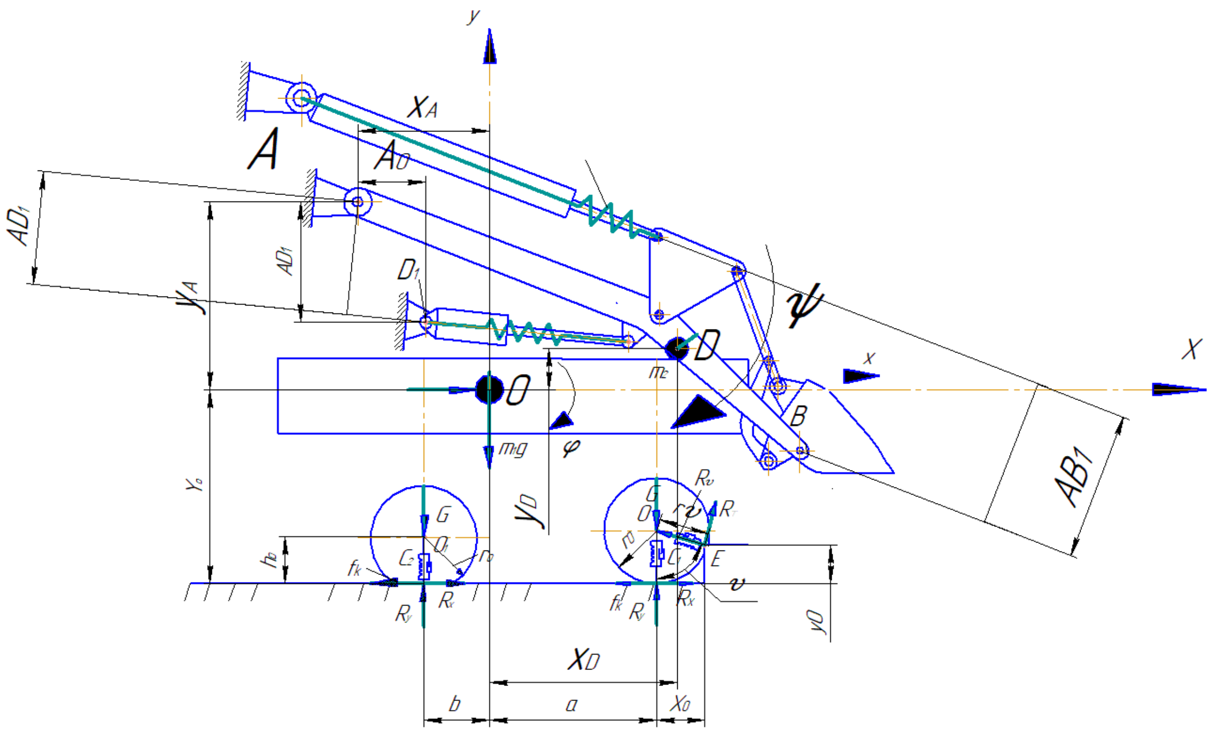

Fig. 1. Mathematical model of the transport mode of a forklift when overcoming a single obstacle

Where:

x and *y* are the current horizontal and vertical coordinates of the loader's centre of mass, respectively;

φ is the current angle of inclination of the longitudinal axis of the loader;

ψ - the current angle of inclination of the working equipment;

m_1 , m_2 are the masses of the skeleton, boom and bucket, respectively;

Rx and *Ry* are the horizontal and vertical reactions in contact of the i-th wheel with the bearing surface, respectively;

Rυ and *Rτ* are the radial and tangential reactions in the contact of the i-th wheel with the obstacle, respectively;

r_υ - the distance from the edge of the obstacle to the axle of the wheel that overcomes the obstacle;

AD_1 is the distance from the axis of the boom lift cylinder to the point of attachment of the boom to the loader chassis;

y_A - the distance from the centre of mass of the forklift to the point where the boom is attached to the machine's chassis;

Y_0 - the height of the centre of mass of the forklift;

y_0 - height of the obstacle;

x_0 - distance from the centre of the wheel to the obstacle;

x_A - distance from point A to the origin of the forklift;

x_D ¬ is the horizontal distance from m_1 to m_2 ;

y_D ¬ vertical distance from m_1 to m_2 .

The progressive movement of the forklift in the direction of the X and Y coordinate axes is described according to the Lagrange equation of the second kind:

$$\frac{d}{dt}\left(\frac{dT}{d\dot{q}}\right)-\frac{dT}{dq}=-\frac{d\Pi}{dq} \qquad (1)$$

The kinetic energy of the entire machine:

$$T=T_0+T_c \qquad (2)$$

where T_o is the kinetic energy of the machine frame; T_c - kinetic energy of the loader boom with a bucket and the levers of the bucket rotation mechanism.

If we consider the initial stage of overcoming the obstacle, which corresponds to the vertical coordinate of the wheel centre, the wheel equilibrium is described by the following system of equations [5]:

$$\begin{Bmatrix} R_v cosv + R_\tau sinv = G_k \\ R_v sinv - R_\tau cosv = P_x \end{Bmatrix} \qquad (3)$$

where R_v is the reaction applied at the point of contact of the wheel with the obstacle.

The value of R_v is determined as follows:

$$R_v=C_r(r_c-r_v) \qquad (4)$$

where r_c is the normal radius; r_v - distance from the centre of the wheel to the point of contact with the obstacle; C_r is the radial stiffness of the tyre at the edge of the obstacle; R_τ is the tangential reaction at the point of contact of the wheel with the obstacle, which is considered positive when it is directed against the direction of rotation of the wheel.

The value of R_τ is determined as follows:

$$R_\tau=\varphi_{сц}\cdot R_v, \qquad (5)$$

where $\varphi_{сц}$ is the coefficient of adhesion of the wheel to the edge of the obstacle.

Since the distance from the centre of the wheel to the point of contact with the bump is not constant and varies with the movement of the forklift, it can be described as follows.

Let's denote the initial position of the wheel centre relative to the forklift's origin as A_x and A_y , and the current position as B_x and B_y

$$\begin{Bmatrix} A_x=(a+x_0) \\ A_y=(Y_0-y_0) \end{Bmatrix} \qquad (6)$$

where a is the initial distance from the origin to the centre of the wheel at ; x_0 - distance from the centre of the wheel to the obstacle; Y_0 - distance from the origin to the reference surface; y_0 - the height of the bump.

Thus, the final system of equations will look like this:

$$(m_1+m_2)\ddot{x}+m_2y_A\ddot{\varphi}+m_2(y_D-y_A)\psi=$$
$$=\left[C_1\cdot(-y+a\cdot\varphi)+\frac{G\cdot a}{a+b}\right]\times$$
$$\times\left(\varphi_{сц}-f_k\right)+\left[C_1\cdot(-y+a\cdot\varphi)+\frac{G\cdot a}{a+b}\right]\cdot\left(\varphi_{сц}-f_k\right)$$

$$-C_1\cdot\sqrt{[\varphi\cdot(Y_0-r_0)-x_0-x]^2+(y-a\cdot\varphi)^2}\times$$
$$\times sinv+\varphi_{сц}\cdot C_1\cdot\sqrt{\begin{matrix}[\varphi\cdot(Y_0-R_0)-x_0-x]^2\\+(y-a\cdot\varphi)^2\end{matrix}}\,cosv;$$
$$(m_1+m_2)\ddot{y}-m_2x_A\ddot{\varphi}-m_2(x_D-x_a)\ddot{\psi}=$$
$$=-G+\left[C_1\cdot(-y+a\varphi)+\frac{G\cdot a}{a+b}\right]+$$
$$\left[C_1(-y-b\varphi)+\frac{G\cdot b}{a+b}\right]+C_1\cdot\sqrt{\begin{matrix}\begin{bmatrix}\varphi\cdot(Y_0-r_0)-\\x_0-x\end{bmatrix}^2+\\+(y-a\varphi)^2\end{matrix}}\times$$
$$\times cosv+\varphi_{сц}\cdot C_1\cdot\sqrt{[\varphi\cdot(Y_0-r_0)-x_0-x]^2+\begin{pmatrix}y-\\a\varphi\end{pmatrix}^2}$$
$$\times sinv;$$
$$m_2y_A\ddot{x}-m_2x_A\ddot{y}+\left[m_2\left(x_A^2+y_A^2\right)+J_1+J_2\right]\ddot{\psi}=$$
$$=-a\begin{bmatrix}C_1\cdot(-y+a\cdot\varphi)\\+\dfrac{G\cdot a}{a+b}\end{bmatrix}+b\begin{bmatrix}C_1\cdot(-y-b\cdot\varphi)+\\\dfrac{G\cdot b}{a+b}\end{bmatrix}+$$

$$+\begin{pmatrix} -C_1\sqrt{\begin{matrix}[\varphi\cdot(Y_0-r_0)-x_0-x]^2+\\+(y-a\varphi)^2\end{matrix}}sinv+ \\ \varphi_{сц}C_1\sqrt{\begin{matrix}[\varphi\cdot(Y_0-r_0)-x_0-x]^2+\\+(y-a\varphi)^2\end{matrix}}cosv \end{pmatrix}\times$$

$$\times\left(Y_0-y_0+y\right)\cdot\varphi\text{-}\begin{bmatrix}C_1\cdot(-y+a\cdot\varphi)\\+\dfrac{G\cdot a}{a+b}\end{bmatrix}\times$$

$$\times\left(\varphi_{сц}-f_k\right)(Y_0+y)\varphi+\begin{bmatrix}C_1\cdot(-y-b\cdot\varphi)+\\\dfrac{G\cdot b}{a+b}\end{bmatrix}\times$$

$$\times\left(\varphi_{сц}-f_k\right)\cdot(Y_0+y)\cdot\varphi;$$

$$m_2\left(y_D-y_A\right)\ddot{x}-m_2(x_D-x_A)\ddot{y}+$$
$$+\left[m_2x_A(x_D-x_A)+m_2y_A\left(y_D-y_A\right)+J_2\right]\ddot{\varphi}+$$
$$+\left[m_2\left(y_D-y_A\right)^2+m_2(x_D-x_A)^2+J_2\right]\ddot{\psi}=$$
$$=\alpha\cdot(AD_1)^2\cdot C_3$$

Conclusions

The developed mathematical models revealed the most dangerous period of interaction between the loader and the supporting surface, namely, the short wheel loader drifting off an obstacle when overcoming it with its rear wheels. The lower the weight of the load in the bucket, the greater the angle of inclination of the loader in the longitudinal plane. For example, the loader's tilt angle reaches a critical point of 25° (at m = 0 kg) and 20° (at m = 1200 kg).

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Study of the interaction of a short-base loader with a supporting surface during transport operations

Abstract. Problem. *The relevance of the work is to create and improve loading and unloading machines.* ***Goal.*** *The article deals with the transport mode of the PMTS 1200 short-base loader, namely the process of moving over a single obstacle.* ***Methodology.*** *Due to the short base and the center of gravity, which is structurally located closer to the rear axle, the machine loses stability when overcoming unevenness in the working surface due to the rear wheels coming off the bearing surface, which reduces its efficiency and productivity.* ***Results.*** *Therefore, there is a need to increase the efficiency of short wheel loaders when overcoming unevenness on the work site by using an intelligent control system in the transport mode, which increases the stability of the machine.****Originality.*** *On the other hand, machine control automation systems require consideration of the transport mode, mathematical modeling of the machine, and algorithmization of work processes, as these parameters are essential for the development of control systems. Thus, the creation of adaptive systems for automatic control of short-base loaders is an urgent scientific and technical problem, the solution of which is of great economic importance for the construction industry.*

Practical value. *Using the developed mathematical models, the dependencies characterizing the interaction of the forklift wheels with the bearing surface were obtained, which are complex in nature but reflect the interaction of a short wheel loader with an obstacle and can be used to assess the stability of the machine and the traction capabilities of its individual wheels.*
Keywords: *short wheel loader; unevenness; stability; working surface; transportation mode.*

Дослідження взаємодії короткобазового навантажувача з опорною поверхнею під час транспортних операцій.

Анотація. Проблема. *Актуальність роботи полягає у створенні та вдосконаленні навантажувально-розвантажувальних машин.* ***Мета.*** *У статті розглядається транспортний режим короткобазового навантажувача ПМТС 1200, а саме процес переїзду через одиночну перешкоду.* ***Методика.*** *Через коротку базу і центр ваги, який конструктивно розташований ближче до задньої осі, при подоланні нерівностей робочої поверхні машина втрачає стійкість внаслідок відриву задніх коліс від опорної поверхні, що знижує її ефективність і продуктивність.* ***Результати.*** *Тому виникає необхідність підвищення ефективності роботи короткобазових навантажувачів при подоланні нерівностей на робочому майданчику за рахунок використання інтелектуальної системи керування в транспортному режимі, що підвищує стійкість машини.* ***Новизна.*** *З іншого боку, системи автоматизації керування машинами потребують врахування транспортного режиму, математичного моделювання машини та алгоритмізації робочих процесів, оскільки ці параметри є суттєвими для розробки систем керування. Таким чином, створення адаптивних систем автоматичного керування робочими процесами короткобазових навантажувачів є актуальною науково-технічною проблемою, вирішення якої має велике народногосподарське значення для будівельної галузі.* ***Практична цінність.*** *За допомогою розроблених математичних моделей отримано залежності, що характеризують взаємодію коліс навантажувача з опорною поверхнею, які мають складний характер, але відображають взаємодію короткобазового навантажувача з перешкодою і можуть бути використані для оцінки стійкості машини та тягових можливостей її окремих коліс.*
Ключові слова: *короткобазовий навантажувач; нерівність; стійкість; робоча поверхня; транспортний режим.*

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