# Design of Agricultural Loader with Articulated Frame

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**Abstract.** The load capacity of the front wheel loader is equal to half the maximum tipping load in the bucket. Therefore, a stability assessment is very important at the design stage. The existing graphical method used to assess the static stability of the loader is very time-consuming and is susceptible to drawing errors. The authors suggest replacing the graphical method with an analytical one. The calculation results revealed that the displacement of the horizontal hinge (balancer) along the frame of the machine does not affect its stability. The loader stability depends solely on the balancer hinge orientation. The mathematical model presented in the article was used in the design of the PK-5 loader manufactured by the Chelyabinsk Tractor Plant. The loader PK-5 has an articulated frame with a combined horizontal and vertical hinges. The use of a combined hinge simplifies the design of the frame and increases the unification of machines based on it. The change in the orientation of the balancer allowed increasing its carrying capacity by 20–30%. The orientation of the balancer completely changed the mechanics of tipping, which increased the safety of the driver.

**Keywords:** Front loader · Articulated frame · Loader loading capacity · Rear balancing frame · Front balance frame · Rollover stability

## 1 Introduction

Articulated wheel loaders are widely used in various sectors of the national economy of all countries of the world. Loading and unloading operations account for 40 … 45% of the total labor costs in agriculture [1], 24% in housing, 47% in road construction, 3% in utilities, 3% in the production of building materials [2], 2% in mining industry [3].

The technological cycle of a front-end loader consists of 57–77% of curved movement (Fig. 1). Therefore, maneuverability is a priority when working in tight spaces. This problem is solved by choosing the right motion control scheme when designing a machine [4].

The presence of cargo in the ladle leads to an increase in the load of the front wheels. This entails an increase in wheel arches, an increase in track and turning radius, as well as complicating steering with steered front wheels. These shortcomings contributed to the emergence and widespread use of the articulated frame scheme for medium and


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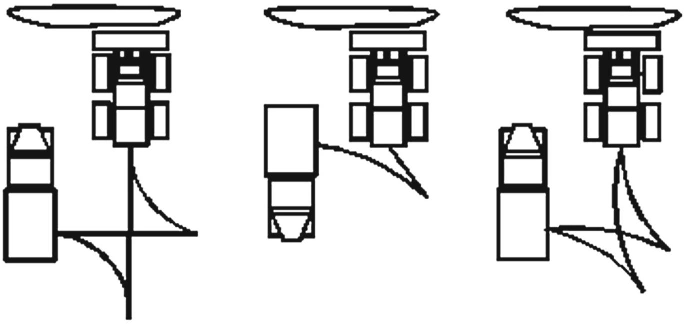

**Fig. 1** Front loader operation examples

heavy front loaders [5]. The hinged frame allows the use of heavy-duty wheels without increasing the overall dimensions of the machine and greatly simplifies the steering control system [6].

The structural scheme of the hinge frame of the loader contains a vertical and horizontal hinge (Fig. 2). These hinges provide rotation of the semi-frames relative to each other in two planes. The vertical hinge rotates one half frames relative to another in the horizontal plane. The folding process of the loader is carried out by hydraulic cylinders.

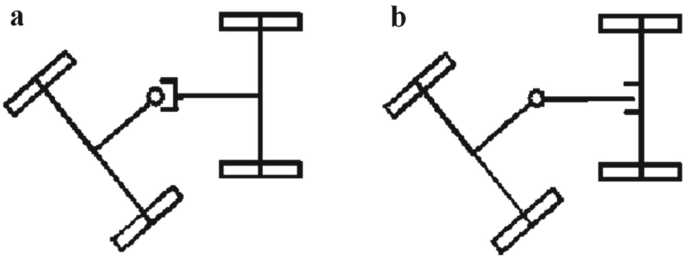


**Fig. 2** Examples of articulated frames with rear balancer (**a**) combined hinge; (**b**) spaced hinge

The horizontal hinge allows one part of the frame to rotate relative to the other in a vertical plane and it is called the balancer. One part of the frame contains a hinge body and is called unbalanced. The other part contains the axis of the hinge and is called the balancer. The balancing part of the frame has the ability to rotate around this axis in a transverse vertical plane.

The vertical hinge and horizontal hinge are combined hinge sometimes (Fig. 2a). The combination hinge greatly simplifies the design of the frame and allows the use of a modular design, which increases the degree of unification of products [7, 8].

The production of special engineering machines is not always justified in Russia. Engineering plants are forced to expand the range of products by creating a family of different special machines on a single energy base. For example, a wheel loader based on the K-700 agricultural tractor was designed at the Kirov Tractor Plant. The Chelyabinsk

Tractor Plant began production of a family of wheeled vehicles with articulated frames for various purposes: a vibration roller, compactor, and front-end loader.

Agricultural articulated tractors K-700 and T-150, working with rear mounted implements, have a rear balancer. Vibration rollers and compactors always have a front balancer. Wheel loaders have different structural schemes today. Some tractor and automobile plants create loaders based on existing tractors. For example, the Amkodor Company produces specialized loaders with a rear balancer. For example, front-end loader K-156 and TO-25 have a front balancer [9]. Which scheme is better?

**The aim of the research** is to study the influence of the structural scheme of the articulated frame on the loading capacity of the loader, the force of normal wheel reactions from the ground and the safety of the driver.

**The object of study** is a structural scheme of an articulated frontal loader PK-5 manufactured by the Chelyabinsk Tractor Plant.

The main characteristic of the loader is its rated load capacity. GOST defines the nominal carrying capacity of the articulated front loader as half the tipping load in the ladle, provided that the half frames are fully folded and the ladle is maximally full. Thus, the performance of the loader significantly depends on the structural scheme determining its static stability.

## 2 Analysis of Previous Studies

The graphic method for assessing the static stability of the articulated joint developed by L.A. Goberman has been widely used at present in Russia [10, 11]. The essence of the method is to build supporting triangles for the balancing and unbalanced parts of the articulated machine, drawing the position of the center of gravity of the machine and the point of application of the tipping force (Fig. 3). The sides of the supporting triangles are axes of tipping.

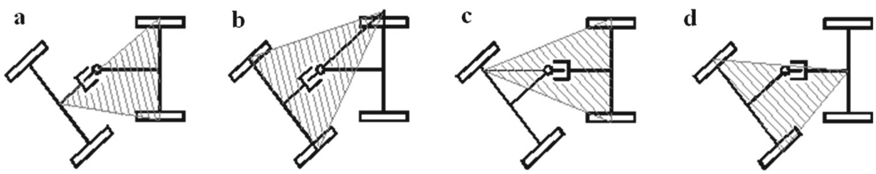


**Fig. 3** Design of the supporting triangles, **a** for the front balancing part, **b** for the rear balancing part, **c** for the front unbalanced part, **d** for the rear unbalancing part

The moment of stability and the tipping moment over are calculated after measuring the necessary force shoulders [12]. The stability moment is calculated as the product of gravity on its shoulder relative to the tipping axis. The tipping moment is calculated as the product of the maximum load in the ladle outside the supporting contour of the machine on its shoulder. The loss of stability is determined when the stability moment equals the tipping moment.

Graphic method has several disadvantages [13]:

- The method is very time-consuming, since the supporting triangles are built separately for each folding angle of the machine;
- Construction is performed only for limiting equilibrium states, and working positions are evaluated only by the safety factor. This approach does not give the full information content of the obtained solution;
- Drawing errors give a significant error;
- The method requires a large amount of computation and drawing for each position;
- The method calculates only the maximum tipping force and does not show the load distribution between the wheels.

## 3 Mathematical Model

The authors proposed an analytical method of the static stability of the front-end loader structural schemes on the laws of mechanics. The mathematical model they constructed does not have the drawbacks listed above [14–16].

The static stability of the loader was determined by the condition of ultimate balance. The equilibrium of an arbitrary system of forces is satisfied provided that the principal vector $\vec{R}_0$ and principal moment $\vec{M}_0$ relative to an arbitrary center are equal to zero:

$$\begin{cases} \vec{R}_o = 0, \\ \vec{M}_o = 0. \end{cases} \quad (1)$$

A scheme of the forces acting on the loader is shown in Fig. 4. The loader is loaded with a system of parallel gravity when working on a horizontal surface.

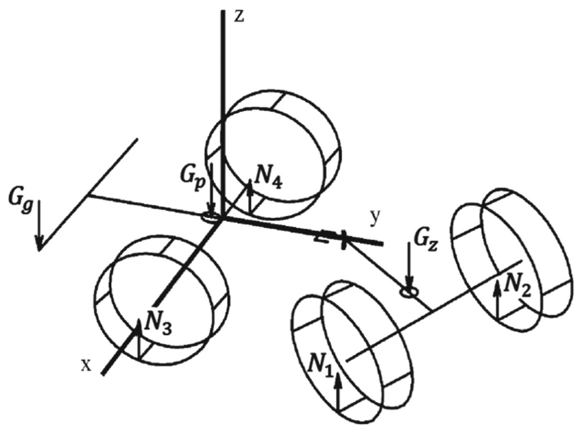


**Fig. 4** Forces scheme

Equilibrium conditions represent three equations:

$\sum F_z = 0$—The sum of the projections of all forces on the vertical axis (the axis is parallel to the forces);

$\sum M_x = 0$, $\sum M_y = 0$—The sum of moments relative to two horizontal axes.

The number of unknown normal reactions from the ground is equal to the number of wheels. We designated the four unknowns as $N_1$, $N_2$, $N_3$, $N_4$ and compiled an additional fourth equation of internal hinge. The absence of friction in this hinge is a basic assumption. The moment equation was written for the rear half frame or for the front half frame depending on the orientation of the balancer. The mathematical model of the static stability of the front loader, taking into account the given dimensions (Fig. 5), has the form:

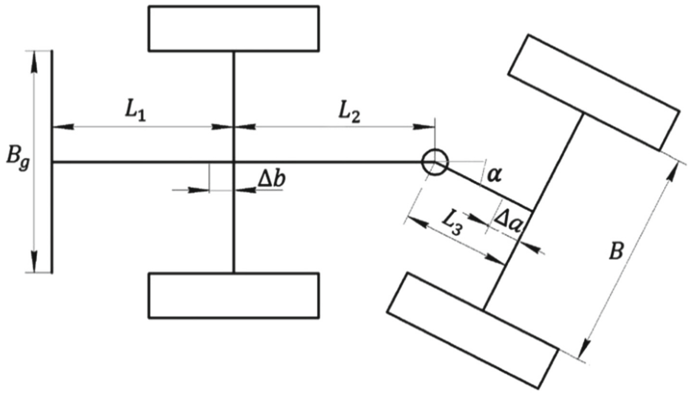


**Fig. 5** Loader design dimensions

$$\sum F_z: \; N_1 + N_2 + N_3 + N_4 - G_z - G_g - G_p = 0 \tag{2}$$

$$\begin{aligned} \sum M_x: \; & - G_z[L_2 + (L_3 - \Delta a)\cos\alpha] + N_1[L_2 + L_3\cos\alpha - 0.5B\sin\alpha] \\ & + G_g L_1 + N_2[L_2 + L_3\cos\alpha + 0.5B\sin\alpha] + G_p\Delta b = 0 \end{aligned} \tag{3}$$

$$\begin{aligned} \sum M_y: \; & - N_1(L_3\sin\alpha + 0.5B\cos\alpha) - N_2(L_3\sin\alpha - 0.5B\cos\alpha) \\ & + G_z(L_3 - \Delta a)\sin\alpha - 0.5N_3B + 0.5N_4B + 0.5G_gB_g = 0 \end{aligned} \tag{4}$$

Additional equation for the front balancer scheme:

$$0.5BN_4 - 0.5BN_3 + 0.5G_gB_g = 0 \tag{5}$$

Additional equation for the rear balancer scheme:

$$0.5BN_1 - 0.5BN_2 = 0 \tag{6}$$

where $B$ is loader track; $B_g$ is ladle width; $L_1$ is the distance from the axis of the front wheels to the ladle; $L_2$ is the distance from the axis of the front wheels to the vertical folding hinge; $L_3$ is the distance from the vertical folding hinge to the axis of the rear wheels; $\Delta a$ is distance from the center of mass of the rear half frame to the axis of the rear wheels; $\Delta b$ is distance from the center of mass of the front half frame to the axis of the front wheels.

## 4 Research Results

The proposed mathematical model (2–6) allowed you to calculate direct problem and inverse problem. **The direct task** is to determine the maximum tipping force in the ladle $G_g\max$. An analytical sign of the beginning of a rollover is the zero reaction of the rear outer wheel $N_2 = 0$. Solving the direct problem is equivalent to estimating the load capacity of the loader [17]. The solution of Eqs. (2–6) allows you to compare different structural schemes of an articulated loader and analyze the effect of linear dimensions on load capacity.

A wheel loader with a rear balancing frame is more stable than for a wheel loader with a front balancing frame at all folding angles (Fig. 6). Its maximum tipping force is 50% greater at a folding angle of 30° and 60% greater at a folding angle of 40°. The performance of a wheel loader is determined by its carrying capacity equal to half the maximum tipping force. Therefore, changing the orientation of the complex hinge from the front balancer to the rear balancer increases the productivity of the loader by 25–30%.

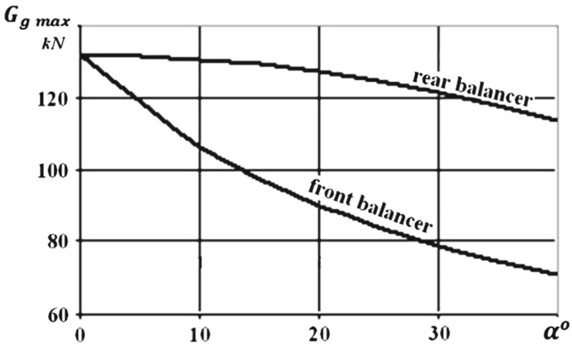


**Fig. 6** Dependence of the maximum tipping force $G_g\max$. in the bucket on the folding angle α°

Analysis of Eqs. (4–5) showed that moving the balancer hinge along the loader frame does not affect the value of the maximum tipping load, all other things being equal. The value of the maximum tipping load depends only on the orientation of the balancer.

**The inverse problem** is to determine the normal wheels reactions at a known load in the ladle. The inverse problem does not solve the problem of stability and load capacity of the loader. However, she is relevant in the analysis of real operating modes. Loads on the wheels of the loader may differ several times when driving in the folded position. This contributes to different operating conditions and different wear of pneumatic tires. The dependence of normal wheel loads on the folding angle is different for a scheme with a rear balance frame and a scheme with a front balance frame (Fig. 7).

The calculation of the inverse problem was performed using the PK-5 loader manufactured by the Chelyabinsk Tractor Plant as an example. The result revealed that wheel loads significantly depend on the structural balancing scheme.

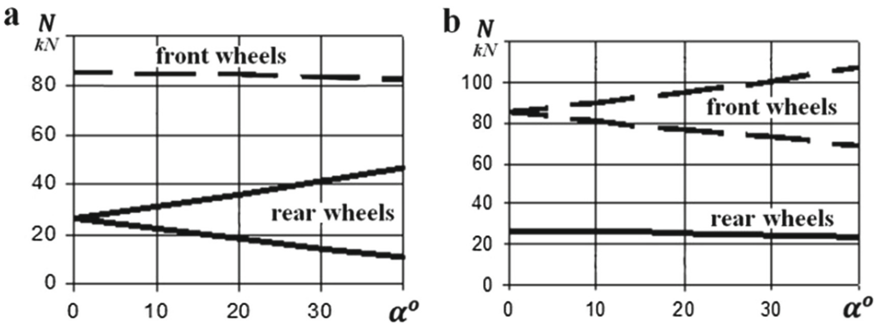


**Fig. 7** Dependence of wheel reactions *N* on the folding angle α° using **a** the front counterweight and **b** the rear counterweight

The rollover static stability determines not only the efficiency of the machine but also the **safety of the driver**, since the rollover mechanics for various structural balancing schemes is fundamentally different [18].

The loader with rear balancing frame flips around the axis of the front wheels. The rear wheels are discharged and take off from the ground at the same time. The cab of the articulated loader is usually mounted on the rear frame, so the driver responds adequately to the loss of stability. The loader with front balancer frame allows the rear frame to rotate relative to the longitudinal axis. This causes the outer rear wheel to separate from the ground. The loader's cab tilts in two planes at once: longitudinal and transverse. Therefore, the safety of the driver of the loader with the front balancer frame is worse than that of the loader with the rear balancer frame. For example, the B138C loader manufactured by the Chelyabinsk Plant of Road-Building Machines based on a grader with the front balancing frame lost stability when folding on a horizontal surface.

The proposed technique was used in the design of the PK-5 loader manufactured by the Chelyabinsk Tractor Plant. Additionally, the impact of centrifugal force and load displacement in the bucket was evaluated. It has been established that centrifugal force increases the stability of the articulated machine with any structural scheme of loader. Lateral displacement of the load in the bucket only leads to the redistribution of loads between the front wheels, while maintaining effort on the rear wheels.

## 5 Conclusions

- The proposed mathematical model made it possible to solve the direct and inverse problems.
- The capacity of the loader with the rear balancing frame is 25–30% higher than the capacity of the loader with the front balancing frame.
- Moving the balancer axis along the loader frame does not affect its stability. Only the orientation of the balancer matters.
- The distribution of normal loads between the wheels can vary by a factor of 2–3 and substantially depends on balancer orientation.
- The rollover mechanics and driver safety are determined by the structural scheme (balancer orientation).

- Lateral displacement of the load in the bucket only leads to the redistribution of loads between the front wheels, while maintaining effort on the rear wheels.
- Centrifugal force increases the stability of the articulated machine with any structural scheme of loader.

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