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## FUNCTIONAL ADAPTATION IN A GRAIN CARRIER WHEN THE MASS OF TRANSPORTED GRAIN IS UNSTABLE

The methodology of functional adaptation of a grain truck by adjusting the speed depending on the density of the transported grain crop is proposed. As a result of studying the functional adaptation of a grain truck with an unstable mass of transported grain, it was found that fluctuations in the grain cargo during transportation significantly affect the stability of the vehicle, especially during maneuvering and braking. When estimating the weight of a grain truck, the density of the transported grain must be taken into account. The volumetric carrying capacity of a grain truck is carefully assessed by establishing a functional dependence on such parameters as nominal carrying capacity, volumetric carrying capacity, body volume, and cargo volume. The dynamic space of grain truck operation is based on a metric state space, each element of which fully determines the state of the system under consideration according to certain functional parameters. If one or more functional parameters of the grain truck are unstable and deviate from their nominal values, the grain truck may lose its functional stability and not perform the functions defined by the regulatory and technical documentation. In such cases, the dynamic operating space is characterised by transfer functions that provide a mathematical basis for analysing the behaviour of the system. During the operation of a grain truck, the task of ensuring its functioning in one of two areas is solved: the area of operation or the area of optimal operation. To ensure that the grain carrier operates in the optimal region, it is necessary to select such nominal values of functional parameters and tolerance fields to ensure the position of the spread and outputs in this region.

**Keywords:** functional adaptation, grain carrier, grain mass, mass instability, acceleration, equation of motion.

### INTRODUCTION

Ukraine is rightly considered a grain country due to the efficient transportation of grain from fields to granaries, from elevators to processing plants, and to seaports. Ukraine has created a KrAZ «Karavan-2» grain haulage train consisting of a KrAZ-6511 C4 dump truck and a PCWi-33 dump trailer with technical and economic indicators on par with foreign analogs (Fig. 1) [1].



Fig. 1 – KrAZ-6511C4 grain carrier

The KrAZ-6511C4 grain truck is equipped with a 400-hp Weichai Power WP12. 400E40 (Euro 4) with SCR exhaust gas cleaning system, MFZ 430 clutch and Fast Gear 12jS180TA manual transmission. The chassis is equipped with a reinforced rear axle balancer suspension, a front axle with an increased payload of up to 8 tonnes, and an integral steering mechanism. The payload of the vehicle is 20 tonnes and the trailer is 24 tonnes.

The results of factory and operational tests confirm the effectiveness of the KrAZ «Karavan-2» grain truck in agricultural enterprises [1].

### ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The applied theory and practice of road train, all-wheel drive vehicle and off-road vehicles are described in [2, 3, 4], on the basis of which the rational values of energy efficiency and parameters of KrAZ

grain carriers during grain transportation are substantiated [5, 6]. However, these works do not reflect the results of studies on the functional stability of an all-wheel drive truck with instability of the transported cargo weight. In [6], the economic efficiency of using the KrAZ «Karavan-2» grain truck train for transporting grain over a distance of 400-500 km was determined and it was found that its use for short distances (up to 50 km) is impractical.

The performance of road trains is determined by their average speed and carrying capacity. The possibilities for increasing the average speed of road trains are limited [7], so the most promising way to increase productivity is to adjust the speed depending on the density of the grain crop (wheat, barley, oats, etc.), i.e. the volumetric carrying capacity ( $t/m^3$ ).

Functionally, vehicle stabilisation is assessed by its dynamic properties, which are manifested in the vehicle's response to control influences [8]. This paper proposes using the value of the acceleration (linear or angular) of a car that occurs when creating a controlling influence as a criterion for controllability. It is proposed to use this criterion to evaluate the dynamic properties of a car not only when turning, but also during acceleration and braking, i.e., controllability is characterized by the accuracy of changing the movement parameters in accordance with the driver's desire. Thus, handling is the ability of a vehicle to respond adequately to driving influences. This manifests the dynamic properties of cars while driving, taking into account the applied forces.

#### PURPOSE AND OBJECTIVES OF THE STUDY

The study aims to develop a methodology for the functional adaptation of a grain carrier by adjusting the speed depending on the density of the transported grain crop.

To achieve this goal, it is necessary to solve the following tasks:

- to substantiate the functional model of a grain truck;
- to develop a methodology for determining the functional stability of a grain carrier when the weight of the transported grain changes;
- to develop practical recommendations for ensuring the functional adaptation of a grain carrier.

#### RESEARCH RESULTS

**Mathematical modeling of grain truck movement.** When a grain truck is moving steadily uphill with an angle  $\alpha$  (Fig. 2), the following forces act on it

- gravity  $G_a$ , applied at the centre of mass  $C_a$  of the vehicle, which can be decomposed into the components  $G_a \sin \alpha$  and  $G_a \cos \alpha$ ;
- the air resistance  $P_w$ , the point of application of which is at the height of the centre of sail, taken equal to the height  $h_c$ ;
- reaction  $P_h$  applied to the mechanism of coupling of the vehicle with the trailer at the height  $h_k$  (it is assumed that  $P_h$  is parallel to the bearing surface);
- normal reactions  $R_1$  and  $R_2$ , shifted by a value  $(n+m)$  from the projection of the wheel axles.

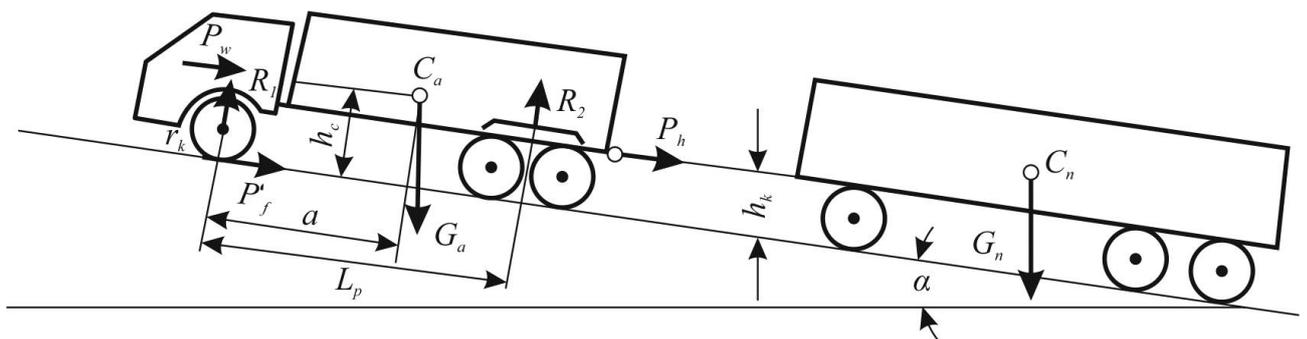


Fig. 2 – Diagram of the forces acting on a grain truck when driving uphill with an angle  $\alpha$

Having compiled the equations of moments of all applied forces relative to the points of applied normal reactions and bearing in mind that the sum of

$$(R_1 + R_2) \frac{n+m}{r_k} = G_a f \cos \alpha,$$

we obtain the following relations for normal reactions:

$$\begin{aligned} R_1 &= G_a \frac{b}{L} \cos \alpha - P_w \frac{h_c}{L} - G_a f \frac{r_k}{L} \cos \alpha - G_a \frac{h_c}{L} \sin \alpha - P_h \frac{h_k}{L}, \\ R_2 &= G_a \frac{b}{L} \cos \alpha + P_w \frac{h_c}{L} + G_a f \frac{r_k}{L} \cos \alpha + G_a \frac{h_c}{L} \sin \alpha + P_h \frac{h_k}{L}. \end{aligned} \quad (1)$$

Neglecting the air resistance ( $P_w=0$ ) and assuming that the driving wheels of the car are the rear wheels, its traction properties are estimated only by the  $R_2$  reaction. Replacing the reaction  $P_h$  of the trailer link in equation (1) with its value:

$$P_h = (l_{fv} - 1)G_a(f \cos \alpha + \sin \alpha) = (l_{fv} - 1)P_a,$$

where  $P_a$  is the traction force on the driving wheels of the vehicle in the absence of the trailing link;  $l_{fv}$  is the vehicle load factor.

In addition, since

$$P_a \frac{h_c}{L} = (G_a \sin \alpha + G_a f \cos \alpha) \frac{h_c}{L},$$

then

$$G_a \frac{h_c}{L} \sin \alpha = P_a \frac{h_c}{L} - G_a f \frac{h_c}{L} \cos \alpha.$$

In this case, transforming equation (1), we obtain

$$R_2 = G_a \frac{a}{L} \cos \alpha + P_a \frac{[h_c(l_{ft} - 1)h_k]}{L} - G_a f \frac{h_c - r_k}{L} \cos \alpha. \quad (2)$$

where  $l_{ft}$  is the trailer load factor.

The expression in square brackets in (2) is the reduced height of the centre of gravity of the grain truck, which is greater the higher the load factor and the height of the hitch. For  $h_k=h_c$  and the value of the load factor  $l_{ft}=D_v$ :  $D_i=2$ , where  $D_v$  and  $D_i$  are the dynamic factors of the vehicle and trailer, respectively. The traction force of the grain truck with the rear drive wheels at the road adhesion coefficient  $\varphi$  is equal to  $P_c=R_2\varphi$ . For this case, the dynamic factor of the grain truck in terms of traction is written as

$$D_c = \frac{a\varphi \cos \alpha}{l_{ft}L\varphi - \varphi[h_h + (l_{ft} - 1)h_k]}. \quad (3)$$

Since the last term of equation (2) is negligible (no more than 0.5 % of  $R_2$ ), the rolling resistance coefficient  $f$  is not included in (3).

The variable forces acting on the grain truck are related either to the displacements or to the velocities of the points of application of these forces. The functional relationship that links the magnitude of the force and the kinematic parameters is the characteristic of the force. The force modulus in this relationship can also be a function of the arguments. For ease of calculation, we will assume that the force modulus is a function of the kinetic parameters for given characteristics.

The equations of motion are used to determine the laws of motion of mechanical systems under given forces [9]. The number of these equations for grain carriers with holonomic links is equal to the number of degrees of freedom of the grain carrier. The equations of motion of a grain carrier can be represented in various forms based on the theorem of change of kinematic energy. In the integral form, the equation of motion of a grain truck has the form:

$$\sum_{i=1}^n T_i - \sum_{i=1}^n T_{i0} = \sum_{k=1}^m A_k, \quad (4)$$

where  $T_{i0}$ ,  $T_i$  are the kinetic energy of the link and the grain truck, respectively, at the beginning and end of the time interval under consideration;  $A_k$  is the work of each of the external and internal forces acting on the grain truck during a given time interval;  $n$  is the number of moving links;  $m$  is the number of forces.

Equation (4) is quite cumbersome even for simple traction units, since it is necessary to summarise the forces. For a grain carrier with one degree of freedom, a simpler form of this equation can be obtained, in

which all summation operations are performed in advance. For this purpose, equation (4) is replaced by the equation of motion of a single point of the grain truck, which moves so that its generalised coordinate coincides at any time with the generalised coordinate of the grain truck. The dynamic model of a grain truck will be a material point with mass  $m_p$  moving under the action of a force  $F_n$  so that the generalised coordinate  $S$  of this point coincides with the generalised coordinate of the grain truck at any given time.

It is always possible to determine such values of  $F_n$  and  $m_n$  that the equation of motion of the actuator point is identical to the equation of motion of the grain truck and, therefore, the generalised coordinate of the actuator point will coincide with the generalised coordinate of the grain truck at any time. In this case, the equation of motion of the fulcrum is written in the form of an energy integral for some finite time interval during which the generalised coordinate changes from  $S_0$  to  $S$ , and the reduced mass (for the grain truck, this value is variable) changes from  $m_n$  to  $m_{n0}$ :

$$\frac{m_n v^2}{2} - \frac{m_{n0} v_0^2}{2} = \int_{S_0}^S F_n dS, \quad (5)$$

where  $v$  is the velocity modulus of the point of reference;  $v_0$  is the value of  $v$  at  $S=S_0$ .

To ensure the identity of equations (4) and (5), it is necessary and sufficient to fulfil the conditions:

$$\int_{S_0}^S F_n dS = \sum_{k=1}^m A_k; \quad (6)$$

$$\frac{m_a v^2}{2} = \sum_{i=1}^n T_i. \quad (7)$$

When the condition in dependence (4) is fulfilled, the condition is also satisfied for any moment of time:

$$\frac{m_{n0} v_0^2}{2} = \sum_{i=1}^n T_{i0}. \quad (8)$$

The reduced force  $F_n$  can be found from (6), and the reduced mass  $m_n$  can be found from (4). Thus, the reduced force is a force conditionally applied to the point of reduction and is determined from the equality of the elementary work of this force to the elementary work of forces and pairs of forces acting on the links of the grain truck (car, trailer). The equality of elementary work simultaneously means the equality of powers of the elements of the grain truck:

$$F_n v = \sum_{i=1}^m N_k, \quad (9)$$

where  $F_k$  is the power of the force (pairs of forces) acting on the grain truck link.

Given the velocity  $v_k$  of the point of application of the force  $F_k$  acting on the grain truck link,  $\omega_k$  of the angular velocity of the grain truck link acted upon by a pair of forces with moment  $M_k$ , the reduced force  $F_n$  is calculated by the formula:

$$F_n = \sum_{k=1}^m \left[ F_k \frac{v_k}{v} \cos(F_k, v_k) + M_k \frac{\omega_k}{v} \right]. \quad (10)$$

This sum can be both positive and negative, i.e., the reduced force is a scalar value. The minus sign indicates that the force  $F_n$  is directed in the opposite direction to the velocity  $v$  of the point of actuation. The reduced force  $F_n$  can be considered as a scalar magnitude that coincides with the generalised Lagrange force, which is determined by the ratio of the sum of the possible work of forces applied to the links of the grain truck. From dependence (7) it follows that the reduced mass of the grain truck can be defined as the mass that the point of actuation must have in order for the kinetic energy of this point to be equal to the kinetic energy of the grain truck's links. The kinetic energy of the link

$$T_i = \frac{m_i v_{si}^2}{2} + \frac{J_{si} \omega_i^2}{2}, \quad (11)$$

where  $m_i$  is the mass of the link;  $v_{si}$  is the modulus of the velocity of the centre of mass of the link;  $\omega_i$  is the modulus of the angular velocity of the link;  $J_{si}$  is the moment of inertia of the link relative to the axis passing through the centre of mass perpendicular to the plane of motion.

Taking into account (11), transforming (7), we obtain the following dependence for estimating the mass of the link

$$m_n = \sum_{i=1}^n \left[ m_i \left( \frac{v_{si}}{v} \right)^2 + J_{si} \left( \frac{\omega_i}{v} \right)^2 \right]. \quad (12)$$

In general, to build a dynamic model of a grain truck, any point on the grain truck can be chosen as the point of reference, i.e. the point where the mass is concentrated. Therefore, the reduced mass of a grain truck can be defined as the mass that must be concentrated at the point of actuation so that the kinetic energy of this point is equal to the kinetic energy of the truck and the grain truck trailer.

The reduced force and reduced mass do not depend on the speed of the point of impact, as the formulas for determining them include only the velocity ratios. For example, if the speed modulus of the point of origin  $v$  changes by a factor of  $k$ , then  $v_k$ ,  $v_{si}$  and  $\omega_i$  change by the same factor, while their ratios to  $v$  remain unchanged. It follows that the determination of the reduced forces and masses can be performed without knowing the velocity of the point of reference, i.e., before solving the equation of motion. This is the main advantage of reduced forces and masses. This conclusion can also be reached by paying attention to the fact that formulas (7) and (8), in addition to the given constants, include only analogues of velocities that do not depend on time.

Let the reduced force  $F_n$  be given as a function of the generalised coordinate  $S$  (displacement of the point of reference). The reduced mass  $m_n$  is a function of the coordinate  $S$ . In this case, to determine the law of motion of the actuator, it is convenient to apply the equation of motion in the form of an energy integral with initial conditions  $t=0$ ,  $S = S_0^{v=v_0}$ . The velocity of the point of reference as a function of the generalised coordinate  $S$  is written as

$$v = v_p = \sqrt{\frac{2}{m_n} \int_{S_0}^S F_n dS + \frac{m_n 0}{m_n} v_0^2}, \quad (13)$$

where  $v_p$  is the operating speed of the grain truck.

In some cases, the integral in the root expression of formula (13) can be represented in the final form. Then, after integration, we will obtain the function  $v=v(S)$  either in the form of a graph or in the form of a series of eigenvalues for changes in displacement  $S$  from  $S_0$  to some value that determines the end of the movement stage under consideration.

When estimating the mass of a grain truck according to dependence (12), it is necessary to take into account the density of the transported grain, which can vary within 300-820 kg/m<sup>3</sup> depending on the moisture content of the grain, temperature and pressure of the medium, as well as the type of grain transported (Table 1).

The relationship between the mass and volume of grain is defined by the formula  $V=m/Q$ , where  $V$  is the volume,  $m$  is the mass (carrying capacity), and  $Q$  is the bulk density of grain.

The dependence of the volumetric carrying capacity of the KrAZ-6511C4 grain truck is estimated by the following parameters:  $Q_n$  - nominal payload of 15.4 tonnes;  $Q_{lc}$  - volumetric payload of 1.3 m<sup>3</sup>;  $V_b$  - body volume of 11.81 m<sup>3</sup>;  $V_c$  - cargo volume of 20.53 m<sup>3</sup>.

**Table 1** – Bulk density of grain crops

№	Name of grain crop	Density, kg/m <sup>3</sup>
1	Wheat	750-850
2	Barley	600-750
3	Oats	400-550
4	Rye	700-750

5	Millet	700-850
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The fuel efficiency of KrAZ grain carriers significantly depends on the volume of transported grain, which was determined during factory tests and by operating organisations using different methods (Table 2) [5].

The test methodology is based on the public road network available near the PJSC «AvtoKrAZ» vehicle manufacturing centre, taking into account the location of road facilities, structures, traffic conditions and terrain. The length of the circular route is 37 km, with sections of traffic in highway and urban conditions, with ascents, descents, bridges, railway crossings, etc. The road surface on the route is asphalt concrete. It is noted that with the increase in the length of the route, the decrease in the density of transported grain crops, fuel consumption decreases (Table 2).

**Functional stability of the grain carrier.** A grain carrier belongs to the class of complex technical systems, the efficiency of which is ensured over a given period of time when performing its general functions within the limits established by regulatory requirements, provided that external destabilising factors are counteracted.

In general, a grain carrier (Fig. 3) is represented as a system with control function vectors  $U(t)$  and disturbance vectors  $F(t)$  as input. The output variables characterising the functional parameters of the grain truck are represented by the vector-function  $Y(t)$ . The dynamic properties of the grain carrier are characterised by the transfer function  $W_r = S_o/S_m$ , where  $S_o$  and  $S_m$  are the output and control parameters, respectively.

**Table 2** – Results of operational tests of the «Karavan-2» road

Tests	Mileage of the road train during testing, km	Transported cargo, cargo weight, t	«Shoulder» of routes, km	Average fuel consumption, l/10 km	Gear ratio of the main gear
1	Total 2505	Corn grain, 48,83-52,66	87-89	53,0-54,6	$i_{mg} = 6,154$
	With cargo 1250	Sunflower seeds, 27,66	182-194	42,0-42,1	
2	Total 2100	Corn grain, 41,72-47,01	66-69	48,2-50,1	$i_{mg} = 4,9$
	With cargo 1050				
3	Total 1737	Corn grain, 48,7	857	42,0-43,1	$i_{mg} = 4,9$
	With cargo 857				
4	Total 1340	Wheat grain, 40,1	280	37,8-38,0	$i_{mg} = 4,9$
	With cargo 560				
5	Total 1320	Organic mix, 35,0	115	35,0-35,3	$i_{mg} = 4,9$
	With cargo 225	Organic mix, 54,0	110	40,0-42,3	

The grain truck is influenced by both controlled input vectors - control functions  $\ell$   $i$  [ $i(t)$  is transmission gear ratio,  $q(t)$  is fuel supply,  $k(t)$  is steering gear ratio,  $p(t)$  is brake control force] and uncontrolled  $m_i$  [ $R(t)$  is driving resistance,  $C(t)$  is road terrain,  $B(t)$  is wind loads, etc.] The output variables  $Y(t)$  are characterised by the driving speed  $v(t)$ , the stability of the direction of movement  $y_d(t)$  and braking  $y_b(t)$ , and the stability of the dynamic properties  $w(t)$  of the grain truck.

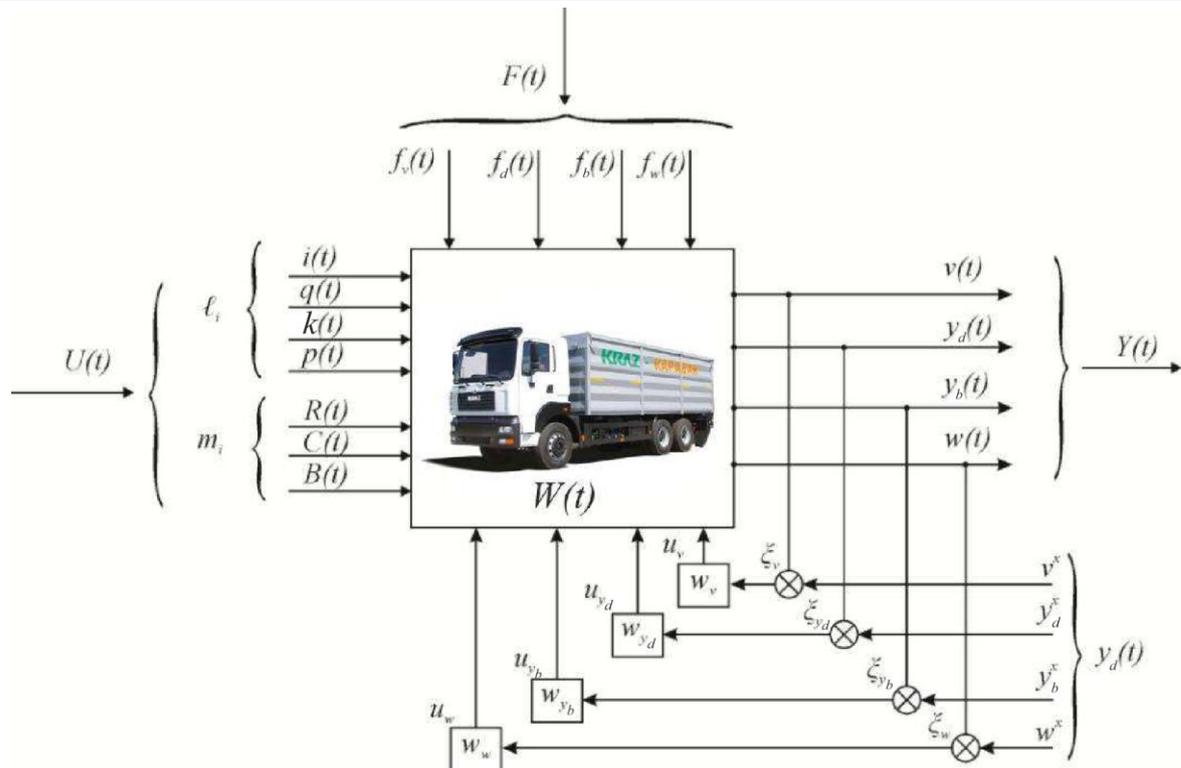


Fig. 3 – Representation of a grain truck as a multidimensional system in a variable state

Typically, disturbances  $F(t)$  are determined by the instability of the output (functional) parameters  $v(t)$ ,  $y_d(t)$ ,  $y_b(t)$ , and  $w(t)$ . When comparing these parameters with their values  $v^x$ ,  $y_d^x$ ,  $y_b^x$  and  $w^x$ , at which the grain carrier operates stably, the controlled input variables  $u(t)$  are adjusted at the comparison links  $\zeta_v$ ,  $\zeta_d$ ,  $\zeta_b$  and  $\zeta_w$ .

The functional parameter  $v(t)$  is characterised mainly by the input control functions  $i(t)$  and  $q(t)$  and determines the operational properties of the grain truck, the parameters  $y_d(t)$  and  $y_b(t)$  are determined mainly by  $v(t)$ , disturbances in the direction of movement  $f_d(t)$  and braking  $f_b(t)$  and are aimed at ensuring the safety of the grain truck. The dynamic parameter  $w(t)$  characterises the movement of a grain truck in the longitudinal, horizontal and vertical planes under the influence of forces in these planes.

The dynamic space of grain truck operation is based on the metric state space, each element of which fully determines the state of the system under consideration by the functional parameters  $v(t)$ ,  $y_d(t)$ ,  $y_b(t)$  and  $w(t)$ . In case of instability of one or more functional parameters of the grain carrier  $v(t)$ ,  $y_d(t)$ ,  $y_b(t)$  and  $w(t)$ , characterised by deviation from the nominal values of  $y^x$ ,  $y_d^x$ ,  $y_b^x$  and  $w^x$ , it is possible that the grain carrier will lose its functional stability, in which case it will not perform the functions defined by the regulatory and technical documentation (R&D). In this case, the dynamic space of grain carrier operation is determined by the transfer functions  $W_v$ ,  $W_{yd}$ ,  $W_{yb}$  i  $W_w$ , characterised by the relationship  $v(t)$ ,  $y_d(t)$ ,  $y_b(t)$ ,  $w(t)$  to  $y^x$ ,  $y_d^x$ ,  $y_b^x$ ,  $w^x$ .

During the operation of a grain truck, the task of ensuring its functioning in one of two areas is solved: *OA* - the area of operation in which the grain carrier operates in accordance with its intended purpose (the required traction force, stability of the direction of movement and braking, etc. are ensured); *AF* - the area of optimal operation, for example, according to the energy saving criterion, in which the grain carrier operates at an acceptable change in speed (change in acceleration within acceptable limits) (Fig. 4).

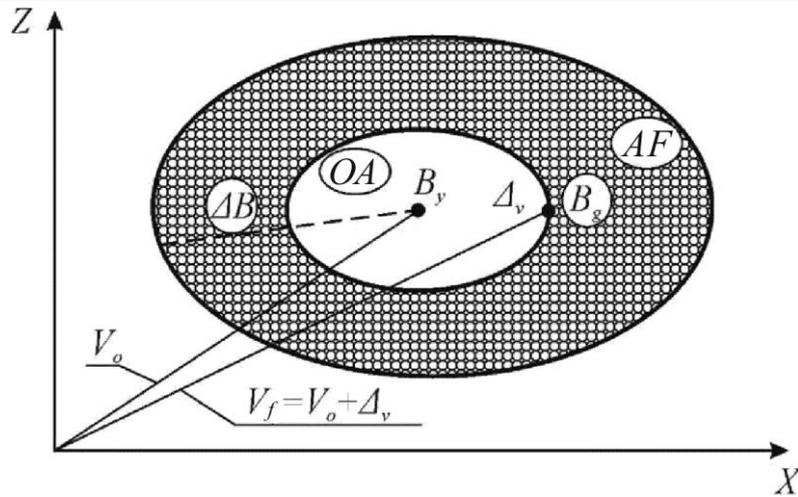


Fig. 4 – Correlation of the areas of optimal operation OA of the grain carrier and the functioning AF of the grain

In this figure, the points B<sub>y</sub> and B<sub>g</sub> indicate, respectively, the operation of a grain truck in an unsteady mode of operation without acceleration and the permissible area for energy saving; Δ<sub>v</sub> is the margin of optimal operation; V<sub>o</sub>, V<sub>f</sub> are the vectors of optimal and actual operation, respectively; ΔB is the margin of operation in the AF region.

Each point of the AF characterises a certain mode of operation of a grain truck at a certain point in time and is described by a certain combination of values of functional parameters, disturbing influences, and the initial state (Fig. 3). The deviation of the point B<sub>g</sub> from the point B<sub>y</sub> (Fig. 4) reflects the margin of optimal functioning Δ<sub>v</sub> of the grain truck

$$\Delta B_z = \frac{z_{jk} - z_{jn}}{z_{jn}} = \frac{\Delta z_j}{\Delta z_{jn}}; \Delta B_x = \frac{x_{ik} - x_{in}}{x_{in}} = \frac{\Delta x_i}{\Delta x_{in}}, \tag{14}$$

where z<sub>jk</sub>, z<sub>jn</sub>; x<sub>ik</sub>, x<sub>in</sub> are the critical values of the studied and boundary parameters along the x, z coordinates; Δx<sub>j</sub>, Δx<sub>i</sub> is the margin of optimal functioning of the grain truck at the value of Δz<sub>jn</sub> and Δz<sub>in</sub>.

The margin of optimal functioning Δ<sub>v</sub> is the deviation of the functioning vector V<sub>f</sub>, whose components are the actual values of the functional parameters, from the nominal vector V<sub>o</sub>, i.e. V<sub>f</sub> = V<sub>o</sub> + Δ<sub>v</sub>. In this case, to ensure the operation of a grain carrier in the optimal area of the OA (according to Fig. 4), it is necessary to ensure the selection of such nominal values of the functional parameters and tolerance fields for them that ensure the position of the spread and outputs in this region.

Given the known requirements for the optimal functioning of the grain carrier in the area of OA, which is determined by the parameters: nominal z<sub>np</sub>, current z and permissible z<sub>vp</sub> (z<sub>np</sub> < z<sub>vp</sub>), the density of distribution of the parameter value, taking into account its spread f<sup>o</sup>(x) and deviation f<sup>v</sup>(x), should be determined:

- the probability that the parameter value will not go beyond the specified tolerances (x<sub>np</sub> < x < x<sub>vp</sub>) during a certain time of grain truck operation, taking into account disturbing influences;
- the tolerance limit (x<sub>np</sub> < x < x<sub>vp</sub>) and the corresponding requirements for the grain carrier not to exceed the probability of the parameter exceeding the tolerance of the specified permissible probability;
- planes f(x) and f<sup>v</sup>(x), under which the conditions that the probability of going beyond the tolerance will be less than the permissible probability will be fulfilled.

**DISCUSSION OF THE RESULTS OF THE STUDY**

To solve this problem, all the functional parameters of the grain carrier are classified by parameters with specified nominal values X<sub>o</sub><sup>C</sup> (Fig. 3 – y<sub>1</sub>(t), y<sub>2</sub>(t), ..., y<sub>n</sub>(t)) and into parameters whose optimal value must be determined X<sub>o</sub><sup>V</sup> (Fig. 4 - the OO region). They are written in vector form:

$$X_o^c = \begin{bmatrix} X_{oi}^c \\ \dots \\ X_{oj}^c \\ \dots \\ X_{oN}^c \end{bmatrix}; X_o^v = \begin{bmatrix} X_{oi}^v \\ \dots \\ X_{oj}^v \\ \dots \\ X_{oM}^v \end{bmatrix} \quad (15)$$

so that any functional parameter of the grain truck is a component of the vectors  $X_o^c$  and  $X_o^v$ .

Predicting the probability of a grain truck being in the optimal region of functioning of the  $OA$  (according to Fig. 4) at time  $t$  is determined by the equations of the Markov process:

$$P_i = v_i P_i(t) + v_{i-1} P_{i-1}(t) \quad (16)$$

under nominal conditions  $i = 0, 1, 2, 3; t_o = 0; P_i(t) = P_i$ .

When assessing the functional stability of a grain truck by only one parameter, for example, by the speed of movement  $v(t)$  (Fig. 3), its functioning can be evaluated by the function  $\bar{x}_v = (v_1, \dots, v_n)$ . The vector  $\bar{x}_v$  corresponds to the number  $R(\bar{x})$ , where  $R(\bar{x}) > 0$  and increases to  $\infty$  at  $\bar{x}_v \rightarrow \bar{v} = (v_1, \dots, v_n)$ , where  $\bar{v}$  is the critical vector.  $R(\bar{x}_v) \rightarrow \infty$  and at  $v_i \rightarrow \bar{V}_i = (V_1, \dots, v_n)$ . In this case  $R(\bar{x}) = [N_i(\bar{x}_v)]^{\pm 1} / [z(\bar{x}_v)]^2$ , where  $i=1,2; \alpha > 0$  is an arbitrary number;  $z(\bar{x}_v) = \prod_{i=1}^n |v_i - V_i|^{q_i}$ ;  $N_i(\bar{x}_v) = \sum_{i=1}^n \alpha_i |v_i - V_i|$  and  $\alpha_i > 0$  is the weighting factor of  $v_i$ ;  $q_i > 0$  is an arbitrary number.

When  $q=1/(n-1)$ ,  $q > \alpha > 1$ , we can write

$$R(\bar{x}_v) = \sum_{i=1}^n \alpha_i |v_i - V_i| \sqrt{\prod_{i=1}^n (v_i - V_i)}. \quad (17)$$

In this case, the functional stability of the grain carrier in terms of the parameter  $v(t)$  is estimated using the following dependence

$$H(\bar{x}_v) = 1/R(\bar{x}_v). \quad (18)$$

This function describes the functioning of the grain truck provided that  $v_i$  reaches the value  $V_i$  when changing  $H(\bar{x}_v)$  within the range from  $H_{max}$  to 0 (when  $v_i = V_i$ ), characterising the functional stability of the grain truck in terms of speed  $v(t)$ .

Similarly, the functional stability of the grain truck can be assessed by the stability of the direction of movement  $y_d(t)$  and braking  $y_b(t)$ , the stability of the dynamic properties  $w(t)$  (Fig. 3). In this case, the critical values of these parameters, which are in the area of the  $AF$  functioning (Fig. 4), are selected according to experimental data based on the method of partial accelerations [10], which is effectively used in assessing the dynamic properties and stability of vehicles [11].

Using the standard form of recording the variable state of a grain truck, we consider its movement as the movement of an autonomous dynamic system when the forces of resistance to movement and the amount of energy used for movement change. This influence usually causes a change in the speed  $v(t)$  of translational motion, which is characterised by equation [12]

$$\frac{dv(t)}{dt} = \frac{P_k - \sum R_c}{m_{ag}}, \quad (19)$$

where  $P_k$  is the moving force of the unit (tangential traction force);  $\sum R_c$  is the sum of the forces of

resistance to the movement of the unit;  $m_{ag}$  is the reduced mass of the unit.

The forces of resistance to the movement of a grain carrier during operation depend on factors, many of which are variable, such as terrain, speed, instability of the mass of transported grain, etc. As the drag forces change, the  $dv/dt$  changes during grain transport. Measurement of the acceleration  $dv/dt$  requires the use of appropriate metrological support for measuring and registration complexes that will allow determining its kinematic and dynamic parameters without interfering with the design of the grain truck [13]. The basis of this complex is capacitive semiconductor three-axis acceleration sensors – accelerometers, which are installed on the car and trailer of the grain truck to assess longitudinal and lateral accelerations.

The combination of the acceleration sensors with the KrAZ-6511C4 navigation system allows to receive on-line and archive information, the analysis of which provides reliable data on the route and modes of movement of the grain truck, instant and average fuel consumption and direction of movement.

## CONCLUSIONS

The study of the functional adaptation of a grain truck with an unstable mass of transported grain revealed that fluctuations in the grain load during transportation significantly affect the stability of the vehicle, especially during manoeuvring and braking. When estimating the weight of a grain truck, it is necessary to take into account the density of the transported grain. The dependence of the volumetric carrying capacity of a grain truck is estimated by the parameters of nominal carrying capacity, volumetric carrying capacity, body volume, and cargo volume.

The dynamic space of grain truck operation is based on the metric state space, each element of which fully determines the state of the system under consideration according to certain functional parameters. If one or more functional parameters of a grain truck are unstable and deviate from their nominal values, the grain truck may lose its functional stability, in which case it will not perform the functions defined by the regulatory and technical documentation. In this case, the dynamic space of grain carrier operation is determined by transfer functions.

During the operation of a grain carrier, the task of ensuring its operation in one of two areas is solved: the area of operation in which the grain carrier operates in accordance with its intended purpose (ensuring the required traction force, stability of the direction of movement and braking, etc.); the area of optimal operation, for example, according to the energy saving criterion, in which the grain carrier operates at an acceptable change in speed (change in acceleration within acceptable limits). To ensure that the grain carrier operates in the optimal range, it is necessary to select such nominal values of functional parameters and their tolerance fields that ensure the position of the spreading and outlet fields in this range.

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***A. Коробко, І. Семенов, Функціональна адаптація зернового при нестабільній масі зерна, що перевозиться***

Запропоновано методику функціональної адаптації зернового шляхом регулювання швидкості залежно від щільності транспортуємої зернової культури. В результаті дослідження функціональної адаптації зернового з нестабільною масою транспортуємої зернової культури встановлено, що коливання зернового вантажу під час транспортування істотно впливають на стійкість транспортного засобу, особливо під час маневрування та гальмування. При оцінці ваги зернового необхідно враховувати щільність транспортуємого зерна. Об'ємна вантажопідйомність зернового ретельно оцінюється шляхом встановлення функціональної залежності від таких параметрів, як номінальна вантажопідйомність, об'ємна вантажопідйомність, об'єм кузова та об'єм вантажу. Динамічний простір експлуатації зернового базується на метричному просторі станів, кожен елемент якого повністю визначає стан розглянутої системи за певними функціональними параметрами. Якщо один або декілька функціональних параметрів зернового нестабільні і відхиляються від номінальних значень, зерновоз може втратити функціональну стабільність і не виконувати функції, визначені нормативною та технічною документацією. У таких випадках динамічний робочий простір характеризується передавальними функціями, які забезпечують математичну основу для аналізу поведінки системи. Під час експлуатації зернового вирішується завдання забезпечення його функціонування в одній з двох областей: області роботи або області оптимальної роботи. Щоб забезпечити роботу зернового в оптимальній області, необхідно підібрати такі номінальні значення функціональних параметрів і поля допусків, щоб забезпечити положення розкиду і виходів в цій області.

**Ключові слова:** функціональна адаптація, зерновоз, зернова маса, нестабільність маси, прискорення, рівняння руху.

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