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METHOD OF COMPUTATION THE PARAMETERS OF CARRYING SYSTEMS OF LIFT AND TRANSPORT MACHINES FOR THE AGRICULTURAL COMPLEX

The conducted theoretical studies consider the most typical calculated cases of dynamic loading of the frames of the load-bearing systems of gantry lifting and transport machines for the agro-industrial complex: movement on the unevenness of the horizontal section of the road; oblique collision with an obstacle; frontal collision with an obstacle. Based on the mathematical model of the dynamic load of the supporting system, a methodology for designing the power elements of the gantry machine has been developed. Taking into account the characteristic modes of movement of the gantry machine, the load dependences of its individual power elements, as well as their groups, were formulated and obtained.

Keywords: *stiffness, load, criterion, case, plane, open profile.*

Проведені теоретичні дослідження розглядають найбільш характерні розрахункові випадки динамічного навантаження рам несучих систем портальних підйомно-транспортних машин для агропромислового комплексу: рух по нерівностях горизонтальної ділянки дороги; косий наїзд на перешкоду; фронтальний наїзд на перешкоду. На підставі математичної моделі динамічного навантаження несучої системи розроблена методика проєктування силових елементів портальної машини. З врахуванням характерних режимів руху портальної машини сформульовані та отримані залежності навантаження окремих її силових елементів, а також їх груп.

Ключові слова: *жорсткість, навантаження, критерій, випадок, площина, відкритий профіль.*

Problem’s Formulation

The basis of the proposed methodology is the most characteristic load modes of the main nodes and aggregates of the portal bearing system, which determine the calculated loads and will be called calculated load cases in the future.

On the basis of the conducted theoretical studies, the following calculation cases of load bearing systems of gantry machines were considered: 1) movement along the unevenness of the horizontal section of the factory road — calculation case for frame spars; 2) oblique collision with a high curb — design case for the frame crossbar and uprights in the transverse vertical plane; 3) frontal collision with a curb 200 mm high by one wheel at a speed of 5 km/h — calculated case for the frame against its folding in its plane and for the rack in the longitudinal vertical plane.

Analysis of recent research and publications

In a number of works, for example, in [1—4], unequivocal recommendations are indicated in favor of the use of open profiles of power elements in the manufacture of frames of load-bearing systems of vehicles. Frames of transport vehicles are generally multi-contour flat-space frame systems. By their very nature, they cannot have high torsional stiffness, when moving over road irregularities, they practically scan these irregularities, twist like a propeller, undergoing significant deformations. So that large deformations are not accompanied by high stresses, it is recommended to make the power elements of such frames from open profiles.

But in the portal bearing system, a specific feature is added to the general picture of load and deformation, associated with the presence of a large concentrated mass in the form of a pallet with cargo on long lifting rods, a container, etc. This is already a dynamic system, prone to fluctuations when driving on bumps in the roads of enterprises, which depend on the dynamic stiffness of the system. In this sense, the stiffness characteristics of the system should be increased in order to move the unstable modes to the zone of practically unattainable movement speeds [4,5].

And if in the longitudinal vertical plane the rigidity can be increased by structural means, in particular, braces, struts, then in the transverse vertical plane it is impossible to do this due to the compositional features of the portal bearing system. Therefore, an increase in rigidity in the transverse vertical plane can be realized only by using spars with closed profiles. At the same time, the natural frequencies of the system increase by an order of magnitude, and the resonant zones shift to the zone of speeds that are not allowed during operation.

An increase in the torsional stiffness of the portal bearing system due to the closed profiles of the spars should be compensated to some extent by a decrease in the torsional stiffness of the crossbars. This means that the cross members of the frame should be made in the form of power elements with an open profile, optimized according to the criterion of minimum torsional stiffness.

Formulation of the study purpose

The article solves the problem of building algorithms for calculating the geometric parameters of the crossbars and frame spars, as well as the verification calculation for the strength of the crossbars and racks of the support system of the portal lifting and transport machine on pneumatic wheels.

Presenting main material

In the gantry bearing system, vertical loads are formed in the process of disturbed movement of the gantry machine in the longitudinal vertical plane. From the pallet with cargo, they are transferred to the spars with the help of load-lifting rods, then, after passing the crossbar, they are transferred to the racks of the supporting system. Thus, in this calculated case, the crossbar is not loaded, the racks work for compression, which is not determinative, and the spars are in pure bending conditions under the effect of calculated vertical forces [6,7]. The task is reduced to the design calculation of the strength of the spar as a two-support statically determined beam, prone to pure bending. The calculation scheme of the spar is presented in fig. 1.

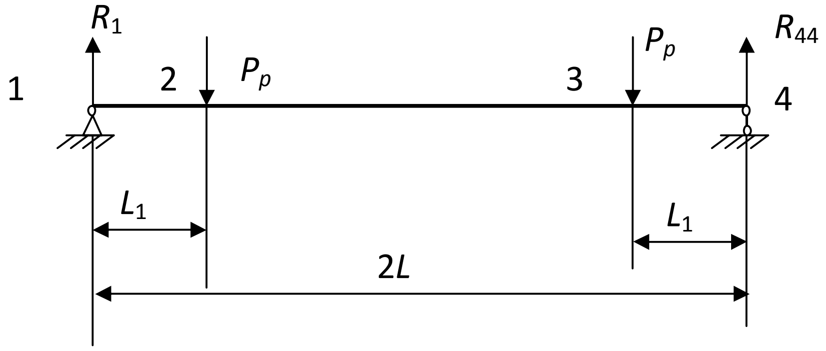

Fig. 1. Calculation scheme of the spar

Reactions ($R_1 = R_4 = P_p$) resistances are determined from the condition of symmetry:

$$Q_y(x)_{1-2} = P_p;\ Q_y(x)_{2-3} = P_p - P_p = 0;\ Q_y(x)_{4-3} = -P_p;$$
$$M_z(x)_{1-2} = P_p x;\ x = 0\ M_z = 0;\ x = L_1\ M_z = P_p L_1;$$
$$M_z(x)_{2-3} = P_p(L_1 + x) - P_p x = P_p L_1;$$
$$M_z(x)_{4-3} = P_p x;\ x = 0\ M_z = 0;\ x = L_1\ M_z = P_p L_1.$$

The maximum stress in the cross section of the spar is equal to

$$\sigma = \frac{M_p}{J_z}\left(\frac{h}{2} + \delta_n\right), \tag{1}$$

where M_p — is the estimated bending moment, Nm; J_z — is the axial moment of inertia of the transverse section of the spar, m^4; h — height of the wall of the cross-section of the spar; δ_n — is the thickness of the side of the cross-section of the spar, m.

In condition (1), the calculated bending moment is determined from the formula

$$M_p = P_p L_1, \tag{2}$$

where

$$P_p = \frac{m_r g}{4}\left\{1 + 48 C_t E J_z m_r h_0 \Omega^2 \Big/ \left[m_r m_к \left(\Omega^2\right)^2 - \left(C_к m_к + 4C_t m_r + C_к m_r\right)\Omega^2 + 4C_t C_к\right]\right\}; \tag{3}$$

$$C_к = 3EJ_z/(3L - 2L_1). \tag{4}$$

In the future, a closed rectangular profile is adopted for the spars; constructively specified by the width of the shelves $в$ and the height of the walls h; the thickness of shelves δ_n and walls δ_c is determined.

For a closed rectangular profile, the axial moment of inertia of the cross section of the spar is equal to

$$J_z = \left(8в\delta_n^3 + 12вh\delta_n^2 + 6вh^2\delta_n + 2h^3\delta_c\right)/12. \tag{5}$$

Condition (1) is written taking into account expressions (2)—(4) and the equation is solved with respect to Jz. Further, in expression (5) in the first approximation, $\delta_c = 0$ is taken, which means the transition to walls that work only in shear, and the cubic equation is solved with respect to δ_n

$$4в\delta_n^3 + 6вh\delta_n^2 + 3вh^2\delta_n - 6J_z = 0. \tag{6}$$

Solving equation (6), the condition $\delta_n \equiv \delta_{n\max}$ is obtained. As the next approximation, $\delta_n = 0{,}9\,\delta_{n\max}$ is taken and substituted into expression (5), which becomes a linear equation with respect to δ_c

$$4в(0{,}9\delta_{n\max})^3 + 6вh(0{,}9\delta_{n\max})^2 + 3вh^2(0{,}9\delta_{n\max}) + h^3\delta_c - 6J_z = 0. \tag{7}$$

Solving equation (7), we get

$$\delta_c = \left[6J_z - 4в(0{,}9\delta_{n\max})^3 - 6вh(0{,}9\delta_{n\max})^2 - 3вh^2(0{,}9\delta_{n\max})\right]/h^3. \tag{8}$$

When a gantry car hits a high curb at an angle, even a small traction force can cause a transverse component force equal to the wheel's grip force with the road surface. In fig. 2 presents a diagram of the formation of lateral forces. The calculated lateral force is taken as the wheel's grip force with the road surface

$$P_z = \frac{mg}{4} f, \tag{9}$$

where m — is the mass of the nominally loaded gantry machine, kg; g — acceleration of free fall, m/s^2; f — is the coupling coefficient.

Forces Pz and bending moments $Mx = PzHк$ act on the frame of the supporting system in the corner sections. Forces Pz can be neglected due to the small values of compressive stresses in the crossbar and bending stresses in the spars. Then the calculation scheme of the frame of the portal bearing system takes the form shown in fig. 3.

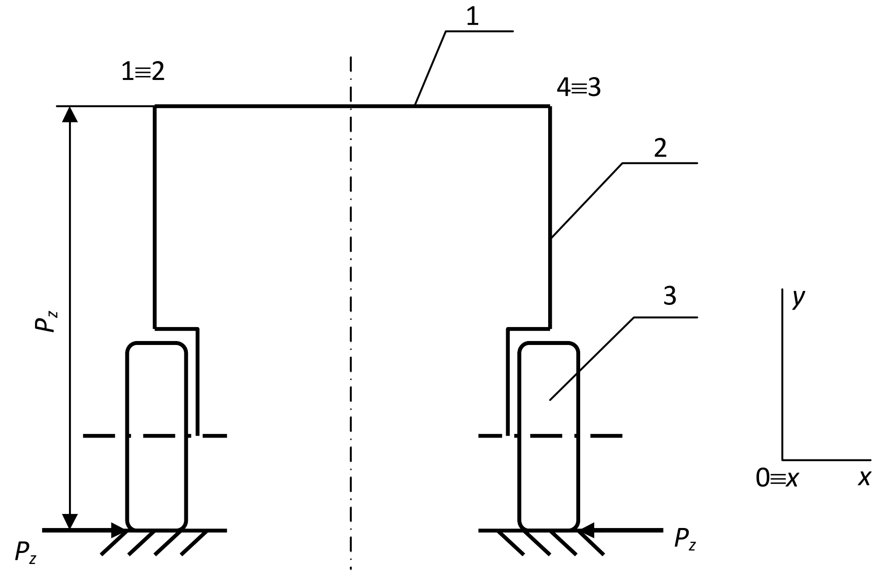

Fig. 2. Scheme of formation of lateral forces on the portal supporting system: 1 — crossbar; 2 — rack; 3 — wheel

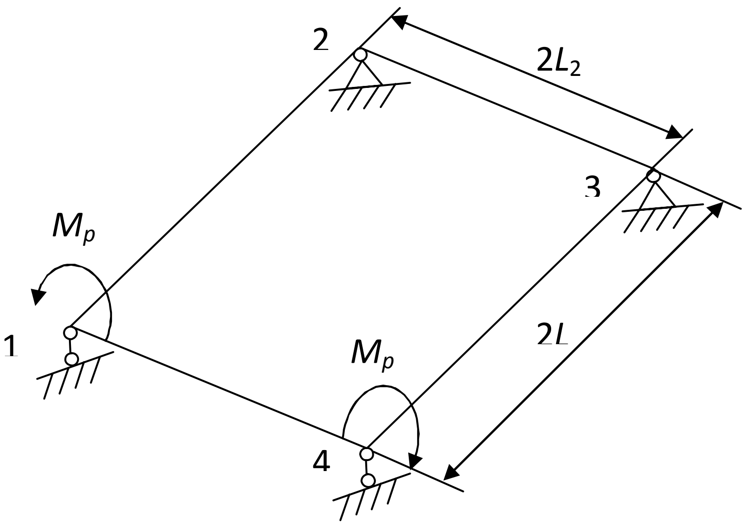

Fig. 3. Calculation scheme of the frame according to the second calculation case

The frame of the portal bearing system according to the second calculation case, taking into account symmetry, is once a statically indeterminate system [8]. The peculiarity of the design calculation of a statically indeterminate frame is that from the condition of strength, not the geometric characteristics of the cross-sections of the force elements are obtained, but their ratio, in particular, taking into account the open I-beam profile of the crossbar:

$$\frac{J_k}{J_{xn}} = \Big\{-\big[4M_pLE(h+2\delta_n)-8[\sigma]L_2GJ_k\big]+ \sqrt{\big[4M_pLE(h+2\delta_n)-8[\sigma]L_2GJ_k\big]^2+64M_pL_2G(h+2\delta_n)[\sigma]LEE_k}\Big\} \Big/ 4M_pL_2G(h+2\delta_n), \tag{10}$$

where J_k — the reduced polar moment of inertia of the cross section of the spar, m^4; J_x — axial moment of inertia of the transverse section of the crossbar, m^4.

The bending moment is determined from the formula

$$M_p = mgfH_\kappa / 4 . \tag{11}$$

Before the stage of determining the relation (10), *Jk* is assumed to be known from the first calculation case. In addition, the width of the shelves and the height of the wall profile of the crossbars are constructively set. Then, in the first approximation, it is assumed that the wall works only in shear, in this case:

$$M_p = mgfH_\kappa / 4 . \tag{12}$$

On the other hand:

$$J_{xn} = \frac{J_\kappa}{\kappa} , \tag{13}$$

where

$$\kappa = \Big\{ -\big[4M_p LE(h+2\delta_n) - 8[\sigma]L_2 GJ_k\big] + \\ + \sqrt{\big[4M_p LE(h+2\delta_n) - 8[\sigma]L_2 GJ_k\big]^2 + 64M_p L_2 G(h+2\delta_n)[\sigma]LEE_k} \Big\} \Big/ \\ - \Big/ 4M_p L_2 G(h+2\delta_n) . \tag{14}$$

By combining expressions (12)—(14), a cubic equation for the thickness of the shelves is obtained:

$$4\text{в}\delta_n^3 + 6\text{в}h\delta_n^2 + 3\text{в}h^2\delta_n - \frac{6J_k}{\kappa} = 0 . \tag{15}$$

Solving equation (15), the condition $\delta_n \equiv \delta_{n\max}$ is obtained. As the next approximation, it is assumed that $\delta_n = 0{,}9\delta_{n\max}$ and a linear equation is obtained with respect to δ_c

$$8\text{в}(0{,}9\delta_{n\max})^3 + 12\text{в}h(0{,}9\delta_{n\max})^2 + 6\text{в}h^2(0{,}9\delta_{n\max}) + \delta_c h^3 - 12J_{xn} = 0 . \tag{16}$$

From (16), we get δ_c

$$\delta_c = \big[12J_{xn} - 8\text{в}(0{,}9\delta_{n\max})^3 - 12\text{в}h(0{,}9\delta_{n\max})^2 - 6\text{в}h^2(0{,}9\delta_{n\max})\big] \big/ h^3 . \tag{17}$$

From fig. 3, it turns out that the calculated bending moment for struts in the transverse vertical plane is determined from the formula

$$M_{xc} = P_z H_\kappa . \tag{18}$$

The maximum stress in the root cross-section (round, hollow) of the rack is associated with the following strength condition [9,10]

$$\sigma = \frac{P_z H_\kappa}{W_{xc}} = \frac{32P_z H_\kappa}{\pi d^3 \left(1 - \alpha^4\right)} \leq [6], \tag{19}$$

where W_{xc} — moment of resistance to bending of the rack in the root section, m^3; d — outer diameter of the root section of the rack, m;

$$\alpha = d_1 / d ,$$

where d_1 — inner diameter of the root section of the rack, m.

Taking constructively α, the outer diameter of the rack is obtained from condition (19)

$$d \geq \sqrt[3]{\frac{32P_z H_\kappa}{\pi\left(1 - \alpha^4\right)[\sigma]}} , \tag{20}$$

or, revealing *Pz* taking into account (12),

$$d \geq \sqrt[3]{\frac{8mgfH_\kappa}{\pi\left(1 - \alpha^4\right)[\sigma]}} . \tag{21}$$

In fig. 4 presents the calculation diagram of the frame of the portal bearing system according to the third calculation case, and shows the diagram of bending moments.

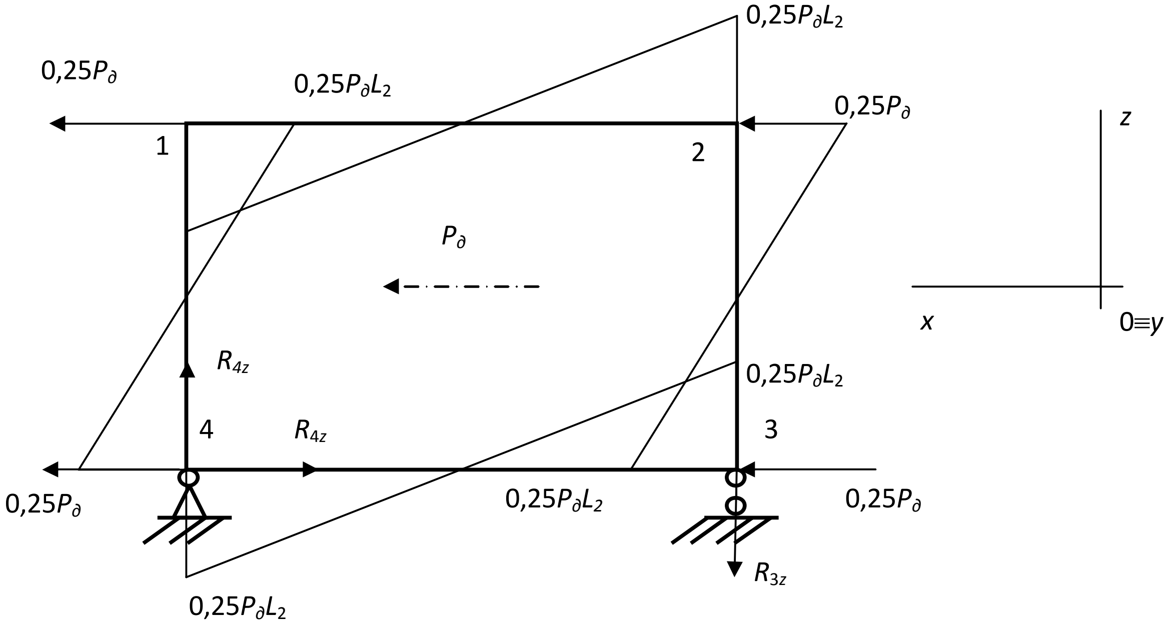

Fig. 4. Calculation scheme of the frame and plot of bending moments

The curve of bending moments is obtained directly from the total curve of bending moments from a unit force by multiplying all coordinates by the P_∂.

Taking into account the closed profile of the spars and the open profile of the crossbars, in particular, the clearly greater bending resistance moment in the plane of the frame of the cross sections of the spars than the crossbar, it can be stated that according to the third calculation case, the crossbars are the weaker link [11]. Therefore, first of all, the condition of strength for the crossbar during bending in the plane of the frame is checked

$$\sigma = \frac{P_p L_2 в}{8 J_{yn}} \le [\sigma], \tag{22}$$

where σ — is the maximum stress in the crossbar during bending in the plane of the frame, Pa; P_∂ — dynamic load according to the third calculation case, N; J_y — axial moment of inertia of cross-section, m^4; y — is the width of the shelves of the I-beam profile of the crossbar, m.

The dynamic load P_∂ is determined from the ratio

$$P_\partial = \upsilon_o \sqrt{m \Big/ \left(\frac{L_2^3}{6EJ_{yn}} + \frac{LL_2^2}{6EJ_y} + \frac{H_c^3}{3EJ_{zc}} + \frac{2LH_c^2}{3EJ_z} + \frac{1}{C_t} \right)}\,. \tag{23}$$

Then the strength condition for the rack in the longitudinal vertical plane is as follows:

$$\sigma = \frac{P_\partial H_c}{W_{zc}} = \frac{32 P_\partial H_c}{\pi d^3 \left(1-\alpha^4\right)} \le [6], \tag{24}$$

where H_c — rack height, m; W_{zc} — the bending resistance moment is stable in the root section, m^3; d — outer diameter of the rack in the root section, m; $\alpha = d_1/d$, where d_1 — вinner diameter of the rack in the root section, m.

If the strength conditions (22) and (24) are not satisfied, the cross-sections of the crossbars and struts are increased, meaning that *Jy* and *Jzc* are included in the dynamic load expression; in addition, the increase in *Jy* should be implemented in such a way that the ratio *Jy*/*Jx* remains unchanged. This is important when revealing the static uncertainty of the frame.

Conclusions

On the basis of the developed mathematical model of static and dynamic load of the load-bearing system of the gantry machine, a methodology for designing its power elements has been developed. The developed method of calculating the parameters of the portal bearing systems is based on the 3 most characteristic load modes of the main nodes of the bearing system: movement along the unevenness of the horizontal section of the road; skew-symmetric collision with a high curb; frontal collision with a curb with one wheel. On the basis of the characteristic modes of movement of the gantry machine, calculated cases of loading of its individual power elements, as well as their groups, are selected and formulated.

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МЕТОДИКА РОЗРАХУНКУ ПАРАМЕТРІВ НЕСУЧИХ СИСТЕМ ПІДЙОМНО-ТРАНСПОРТНИХ МАШИН ДЛЯ АГРОПРОМИСЛОВОГО КОМПЛЕКСУ

Реферат

У роботі наведені особливості запропонованої методики розрахунку параметрів елементів несучих систем підйомно-транспортних портальних машин які використовуються в логістичних процесах в агропромисловому комплексі. В несучій системі підйомно-транспортних машин портального типу до загальної картини навантаження і деформації додається специфічна особливість, пов'язана з наявністю великої зосередженої маси у вигляді піддону з вантажем на довгих вантажопідйомних штангах, контейнера і т.п. Ця динамічна система схильна до коливань при русі по нерівностях доріг та різноманітних перешкод. Коливання залежать від динамічної жорсткості системи і ці жорсткістні характеристики системи слід збільшувати, щоб нестійкі режими відвести в зону практично недосяжних швидкостей руху, таким чином увести розрахункову систему у дорезонансні або резонансні частоти.

Збільшення жорсткості в поперечній вертикальній площині можна реалізувати застосуванням лонжеронів із закритими профілями. При цьому власні частоти системи збільшуються на порядок, а резонансні зони зміщуються в зону швидкостей, які не допускаються при експлуатації. В повздовжній вертикальній площині конструктивну жорсткість портальної системи можна збільшити введенням конструктивних засобів.

Розроблена методика розрахунку параметрів портальних несучих систем базуються на 3-х найхарактерніших режимах навантаження основних вузлів несучої системи: рух по нерівностях горизонтальної ділянки дороги; кососиметричний наїзд на високий бордюр; фронтальний наїзд на бордюр одним колесом. На підставі характерних режимів руху портальної машини виділені і сформульовані розрахункові випадки навантаження окремих її силових елементів, а так само їх груп.

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