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ENERGY AND INTEGRATED METHOD IN EVALUATION OF WORKING LIFE OF SUPPORTING SYSTEMS FOR MOBILE AGRICULTURAL MACHINES

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Summary. *This paper analyzes the structural uncertainty disclosure of static structures modified by potential energy minimum deformation (MMPED). In general, the potential energy of deformation consists of several components, namely energy from stretching-compression deformation, cut, bend and torsion. It is shown that the potential energy of deformation tension-compression does not significantly affect the results of the calculation, so they are mostly ignored [1]. For constructions whose elements consist of open profiles, in most cases the solution depends on the total potential energy of deformation of torsion, which decomposes into potential energy and compressed pure twisting. Significant simplification in the formation of the system of canonical equations has been made by the use of some properties of integral calculus.*

Keywords*: potential energy of deformation, bending, twisting, frame, bimoment.*

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Problem setting. The development of analytical methods for calculating the stress-strain state of constructive bearing structures, including mobile agricultural machines, that is the disclosure of the static uncertainty in relation to external supports and internal power factors, clearly require further improvements.

In many cases the most destructive load is a load-bearing frame, which is mainly equipped with public profiles of torsion. We consider the more complex deformation process of loading, consisting of pure torsion and so-called compressed torsion. Potential energy of deformation in this case is solely from bimoment B_ω. In addition, a specific example shows the actual design feature and effectiveness of this type of loading. It has also been researched that this strain energy of structural system is the dominant uncertainty in the disclosure of the static structural systems whose elements consist of open profiles.

Analysis of recent research and publications. Advantages of MMPED, compared with the traditional numerical methods, are grounded in the simplicity of algorithms, the possibility of obtaining results without any additional complications [2]. The stress-strain state of MMPED frame structures has been studied in [3], [4] and experimental confirmation by strain gauges has been conducted.

The purpose of the article is to develop energy-integral method for estimating the life of the bearing of mobile agricultural machinery in a dynamic tasks setting. For structural system, which consists of an open structure elements, given the complex stress-strain process, the task is determine the potential energy of bending, twisting and deplanation deformations. In addition, it has been researched how a potential energy of deplanation has a dominant influence on the disclosure of static uncertainty and automated formation of canonical equations. It is worth mentioning that the application of the rule of integrand Leibniz differentiation of power functions significantly simplifies the solution of such problems. It is necessary to calculate linking elements of bearing systems consisting of open profiles.

Objectives setting. It is necessary to calculate the frame structure loaded with asymmetric loads considering different energies of deformation. The second objective is to calculate weld coupling in a dangerous intersection. Then an integrated energy resource evaluation method of agricultural machinery in a dynamic tasks setting should be created.

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Research results. In engineering, namely in mobile agricultural, elements of supporting systems primarily are coupled with welded seams. In the nodes of the connections of various types of profiles that make up the whole bearing structural system, there are complex deformations which are in engineering classified as compressed torsion. The peculiarity of the compressed torsion is the actual mode of deformation which occurs in the joints as a result of bending and twisting moments. Such deformation mechanical process in engineering is described as bimoments, that is bipair moments which are marked as B_ω. Referring to the power method of the set problem, the deformation energy of the compressed torsion is generally recorded as [1]:

$$U_{B_\omega} = \sum_1^n \int_l \frac{B_{\omega i}^2 ds}{2EI_{\omega i}}, \tag{1}$$

where n – the number of sections into which the proposed bar system is divided; $B_{\omega i}$ – bipair moment of the i element, $\mathrm{H} \cdot \mathrm{m}^2$; E – Young's module, H/m^2; $I_{\omega i}$ – sectorial moment of inertia i element, m^6.

We used the relation (1) and Kastylyano's theorem in which the partial derivative of potential energy at the specified power factor determines the movement in the intersection of power factor. When considering statically indeterminate structures design with unknown redundant internal power factors on the basis of the theorem about the least workload, movements in the section turns into a minimum that is zero, we get the dependence:

$$\frac{\partial U_{B\omega}}{\partial X_i} = 0. \tag{2}$$

To calculate partial derivatives of the total potential energy (1), we use dependence (2) and form a system of equations.

Thus, to determine X_i of the unknown (i = 1 ... n), we obtain an advantageous system of canonical equations of the unknown. An element of integration potential energy functions strain are functions of the second degree, whose solution is complicated by the classic method. To simplify the solutions of equations (2), we use Leibniz's rule which is easily converted into an algorithm during integrand functions with differentiation [1]:

$$\frac{\partial \left[\int_0^b f(s,\alpha) ds \right]}{\partial \alpha} = \int_0^b \left[\frac{f(s,\alpha)}{\partial \alpha} \right] ds. \tag{3}$$

That is, if the integrand consists of parameters and variables, it independently can be differentiated according to α parameter and integrate with the variable s.

In a modification of the minimum potential energy of deformation using another characteristics of calculus of appointed integrals, i.e. the integral sum (difference) equals to the sum (difference) of integrals:

$$\int_0^b (c \pm k \pm ... \pm n) s ds = \int_0^b c \cdot s \cdot ds \pm \int_0^b k \cdot s \cdot ds \pm ... \pm \int_0^b n \cdot s \cdot ds. \tag{4}$$

It is the most appropriate to show the effectiveness of the above and other provisions in specific example which will be considered in this article (Fig. 1).

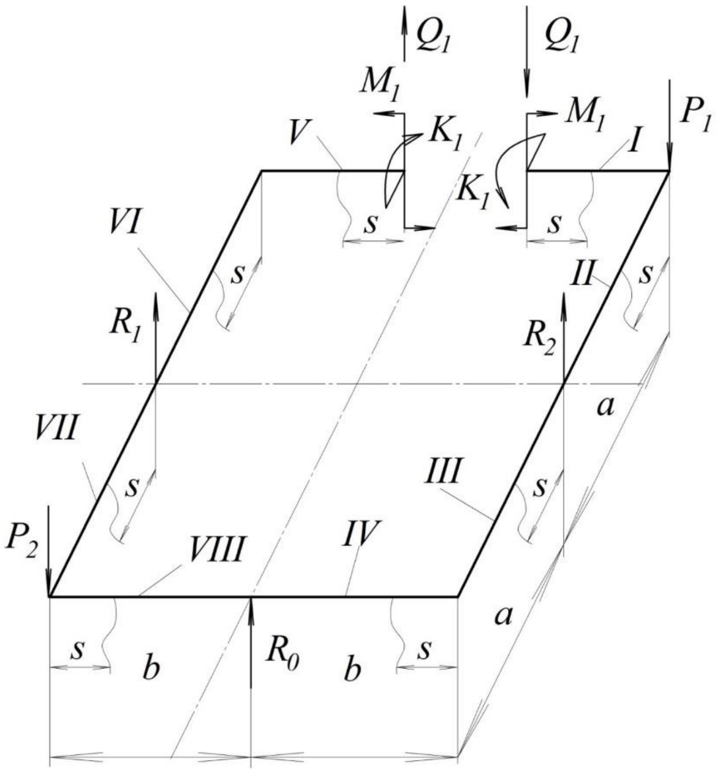

Figure 1. Schematization of loads on the structural system: P_1=*1200H*, P_2=*1000H*, R_1=1100H, R_2=1300H, I_K=3,634 · $10^{-8}m^4$, I_o =*436 ·* $10^{-8}m^4$, I_ω =*768,3 ·* 10^{-12} m^6, *E=2,1 ·* 10^{11} *Pa, G=8 ·* 10^{10} *Pa, k=4,245.*

Functions of bending and twisting moments are recorded within internal power factors and output for external loads of two parts of the given system. The current scheme (Figure 1) shows that the internal power factors K_1, M_1, Q_1 are equal in magnitude and opposite in their signs.

The right side of the structural system, areas I, II, III and IV (Fig. 1) record moments functions:

I area, $0 \le s \le b$:
$$M(s) = M_1 - Q_1 \cdot s;$$
$$K(s) = K_1.$$

II area, $0 \le s \le a$:
$$M(s) = K_1 - Q_1 \cdot s - P_1 \cdot s;$$
$$K(s) = -M_1 + Q_1 \cdot b.$$

III area, $0 \le s \le a$:
$$M(s) = K_1 - Q_1 \cdot s - Q_1 \cdot a - P_1 \cdot s - P_1 \cdot a + R_2 \cdot s;$$
$$K(s) = -M_1 + Q_1 \cdot b.$$

IV area, $0 \le s \le b$:
$$M(s) = -M_1 + Q_1 \cdot b - Q_1 \cdot s - P_1 \cdot s + R_2 \cdot s;$$
$$K(s) = -K_1 + Q_1 \cdot 2a + P_1 \cdot 2a - R_2 \cdot a. \qquad (5)$$

The left side of the structural system, areas V, VI, VII i VIII (Fig. 1):

V area, $0 \le s \le b$:
$$M(s) = M_1 + Q_1 \cdot s;$$
$$K(s) = K_1.$$

VI area, $0 \le s \le a$:
$$M(s) = -K_1 + Q_1 \cdot s;$$
$$K(s) = M_1 + Q_1 \cdot b.$$

VII area, $0 \le s \le a$:
$$M(s) = -K_1 + Q_1 \cdot s + Q_1 \cdot a + R_1 \cdot s;$$

VIII area, $0 \le s \le b$:
$$M(s) = -M_1 - Q_1 \cdot b + Q_1 \cdot s - P_2 \cdot s + R_1 \cdot s;$$

$K(s) = M_1 + Q_1 \cdot b.$ $\qquad\qquad$ $K(s) = -K_1 + Q_1 \cdot 2a + R_1 \cdot a.$ (6)

The total potential energy of bending and torsion deformations in both parts of the frame is the following:

$$U = U_M + U_K = \sum_{i=1}^{8} \int_0^s \frac{[M(s)_i]^2}{2EI_o} ds + \sum_{i=1}^{8} \int_0^s \frac{[K(s)_i]^2}{2GI_K} ds. \tag{7}$$

The internal power factors when torsion is compressed in any cross section of the rod frame are determined by the function of angular deformation $\theta(s)$ ad recorded by differential equations [5]:

$$M_K(s) = GI_K \theta'(s); \quad B_\omega(s) = -EI_\omega \theta''(s); \quad M_\omega = GI_\omega \theta'''(s), \tag{8}$$

M_K – pure torsional moment; B_ω – bimoment; M_ω – flexion-torque moment.

Mounting of cross beams to longitudinal longerons within frames, eg mobile agricultural machines, eliminates deplanation of transverse beam at the intersection of its accession to the spar and at the crossroads junction of longitudinal spars. This allows to consider transverse beams as console tightly pinched at one end, and the longitudinal longeron as a single console beam also pinched at one end and loaded with torque fixing at its cross beams. We disregard the influence of cross beams bimoments on longerons. This simplifies recording of bimoments functions [1].

Generalized bimoments equation for a single *i*-element of the frame construction is:

$$B_\omega(s)_i = \frac{K_i}{k} \frac{sh(k \cdot s)}{ch(k)}; \; k = \sqrt{\frac{G \cdot I_K}{E \cdot I_\omega}}. \tag{9}$$

k – flexion-torque characteristic of the rod stiffness

Potential energy of deplanation of the examining system and the whole structure is:

$$U_{B_{\omega i}} = \int_0^s \frac{B_{\omega_i}^2 ds}{2EI_\omega}; \qquad U_{B_\omega} = \sum_{i=1}^{8} U_{B_{\omega i}} \tag{10}$$

We conduct determination of unknown internal power factors M_1, K_1, Q_1 for three cases of potential energy deformation, namely:

$$U = U_M + U_K; \tag{11}$$

$$U = U_K; \tag{12}$$

$$U = U_{B_\omega}. \tag{13}$$

The systems of equations are formed using the method of potential energy minimum:

$$\frac{\partial (U_M + U_K)}{\partial X_i} = 0; \qquad \frac{\partial U_K}{\partial X_i} = 0; \qquad \frac{\partial U_{B_\omega}}{\partial X_i} = 0. \tag{14}$$

Using potential energy of torsion deformation (12) and the relationship (5) and (6) we will show a modification MMPED with Leibniz's rule:

$$U_K = \int_0^b \frac{[K_1]^2}{2GI_K}ds + \int_0^a \frac{[-M_1 + Q_1 \cdot b]^2}{2GI_K}ds + \int_0^a \frac{[-M_1 + Q_1 \cdot b]^2}{2GI_K}ds + \int_0^b \frac{[-K_1 + Q_1 \cdot 2a + P_1 \cdot 2a - R_2 a]^2}{2GI_K}ds + \\ + \int_0^b \frac{[K_1]^2}{2GI_K}ds + \int_0^a \frac{[M_1 + Q_1 \cdot b]^2}{2GI_K}ds + \int_0^a \frac{[M_1 + Q_1 \cdot b]^2}{2GI_K}ds + \int_0^b \frac{[-K_1 + Q_1 \cdot 2a + R_1 \cdot a]^2}{2GI_K}ds. \tag{15}$$

According to Leibniz's rule, we differentiate degree integrand:

$$\frac{\partial(U_K)}{\partial M_1} = \int_0^a \frac{2[-M_1 + Q_1 \cdot b]\cdot(-1)}{2GI_K}ds + \int_0^a \frac{2[-M_1 + Q_1 \cdot b]\cdot(-1)}{2GI_K}ds + \int_0^a \frac{2[M_1 + Q_1 \cdot b]}{2GI_K}ds + \\ + \int_0^a \frac{2[M_1 + Q_1 \cdot b]}{2GI_K}ds = 0;$$

$$\frac{\partial(U_K)}{\partial K_1} = \int_0^b \frac{2[K_1]}{2GI_K}ds + \int_0^b \frac{2[-K_1 + Q_1 \cdot 2a + P_1 \cdot 2a - R_2 a]\cdot(-1)}{2GI_K}ds + \int_0^b \frac{2[K_1]}{2GI_K}ds + \\ + \int_0^b \frac{2[-K_1 + Q_1 \cdot 2a + R_1 \cdot a](-1)}{2GI_K}ds = 0; \tag{16}$$

$$\frac{\partial(U_K)}{\partial Q_1} = \int_0^a \frac{2[-M_1 + Q_1 \cdot b]\cdot b}{2GI_K}ds + \int_0^a \frac{2[-M_1 + Q_1 \cdot b]\cdot b}{2GI_K}ds + \int_0^b \frac{2[-K_1 + Q_1 \cdot 2a + P_1 \cdot 2a - R_2 a]\cdot 2a}{2GI_K}ds + \\ + \int_0^a \frac{2[M_1 + Q_1 \cdot b]\cdot b}{2GI_K}ds + \int_0^a \frac{2[M_1 + Q_1 \cdot b]\cdot b}{2GI_K}ds + \int_0^b \frac{2[-K_1 + Q_1 \cdot 2a + R_1 \cdot a]\cdot 2a}{2GI_K}ds = 0;$$

and solve a system of equations:

$$\int_0^a [M_1 - Q_1 \cdot b]\cdot ds + \int_0^a [M_1 - Q_1 \cdot b]ds + \int_0^a [M_1 + Q_1 \cdot b]ds + \int_0^a [M_1 + Q_1 \cdot b]ds = 0;$$

$$\int_0^b K_1 ds + \int_0^b [K_1 - Q_1 \cdot 2a - P_1 \cdot 2a + R_2 a]ds + \int_0^b K_1 ds + \int_0^b [K_1 - Q_1 \cdot 2a - R_1 \cdot a]ds = 0;$$

$$\int_0^a [-Mb_1 + Q_1 \cdot b^2]ds + \int_0^a [-Mb_1 + Q_1 \cdot b^2]ds + \int_0^b [-K_1 2a + Q_1 \cdot 4a^2 + P_1 \cdot 4a^2 - 2R_2 a^2]ds + \\ + \int_0^a [M_1 b + Q_1 \cdot b^2]ds + \int_0^a [M_1 b + Q_1 \cdot b^2]ds + \int_0^b [-K_1 2a + Q_1 \cdot 4a^2 + R_1 \cdot 2a^2]ds = 0. \tag{17}$$

We provide enumeration of internal power factors for the cases (14). The calculation results are shown in Table 1.

Table 1.
The results of the calculation of the frame construction

	M_1	K_1	Q_1
$U_M + U_K$	0.47	551	-2199.2
U_K	0	550	-2200
U_{B_ω}	0	550	-2200

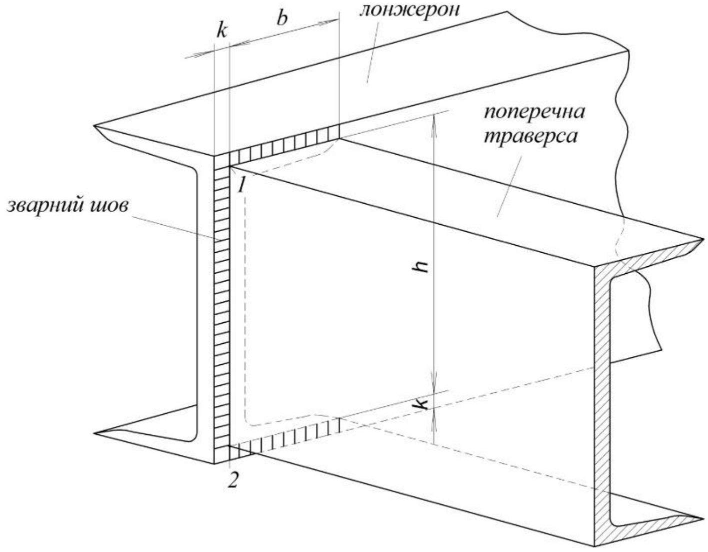

Figure. 2. Front weld coupling of the frame construction elements

Calculation of the weld seam has been made in the intersection of cross-arm (channel) joining to longeron frame (Figure 2). In the considered coupling there is a complex stress-strain state of: Q – cutting force, M – bending moment, M_K – pure torsional moment, B_ω – bipair moment, M_ω – flexion-torque moment (Figure 3).

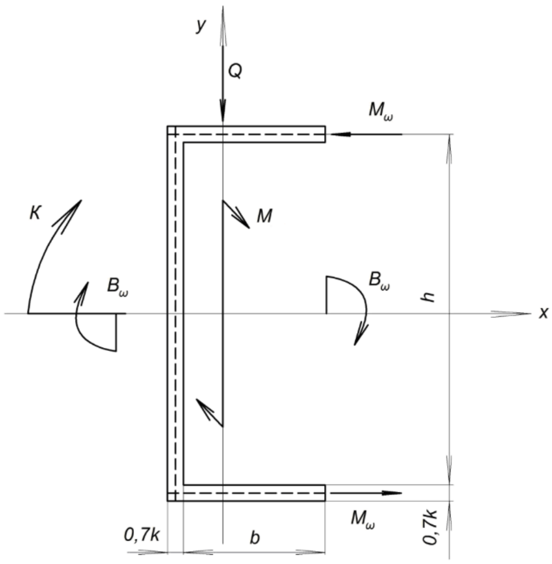

Figure. 3. Schematization of internal power factors of weld coupling: $Q = 2200H$, $M = 1100H \cdot м$, $K = 550H \cdot м$, $B_\omega = 15{,}0H \cdot м^2$, $M_\omega = 66{,}0H \cdot м$, $M_K = 484H \cdot м$

The destruction of the weld seam in this summary is due to the bisector planes cut. Height of cut plane is 0,7 k. In this case there are only shear stresses in the fracture plane whose vectors are identical to internal power factors.

We analyse stress-strain of the weld coupling state (Figure 2) and (Figure 3). In this case only the extreme points of intersection of the weld coupling are dangerous, ie, points 1 and 2. The maximum shear stress points according to the settings of the profile are:

$$\tau_{\max} = \sqrt{46{,}3^2 + 71{,}8^2} = 85{,}4 МПа .$$

Conclusions. The proposed energy-integral method for estimating the life of the bearing of mobile agricultural machines shows that the bimoment impact is dominant on its mode of deformation. An updated calculation of the weld coupling considering internal force factors arising in compressed twist.

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ЕНЕРГЕТИЧНО ІНТЕГРАЛЬНИЙ МЕТОД ОЦІНКИ РЕСУРСУ РОБОТИ НЕСУЧИХ СИСТЕМ МОБІЛЬНИХ СІЛЬСЬКОГОСПОДАРСЬКИХ МАШИН

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Резюме. *Проведено аналіз розкриття статичної невизначеності конструктивних структур модифікованим методом мінімуму потенціальної енергії деформації (ММПЕД). У загальному випадку потенціальна енергія деформації складається з кількох складових, а саме, енергій від деформацій розтягу-стиску, зрізу, згину та кручення. Показано, що потенціальні енергії деформацій розтягу-стиску не суттєво впливають на результати розрахунку, тому ними переважно нехтують [1]. Для конструкцій елементи яких складаються з відкритих профілів у більшості випадків розв'язок залежить лише від потенціальної енергії деформації загального кручення, яка розкладається на потенціальні енергії чистого кручення та стисненого кручення. Значне спрощення при формуванні системи канонічних рівнянь дало, використання окремих властивостей інтегрального числення.*

Ключові слова*: потенціальна енергія деформації, згин, кручення, рама, бімомент.*

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