Određivanje opterećenja hodnog stroja buldozera usled podužnog nagiba

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Na osnovu simulacije zglobnih mašina - točkaša izrađen je matematički model buldozera za sve njegove režime rada. Predloženi matematički model primenjen je za određivanje opterećenja hodnog stroja buldozera usled podužnog nagiba.

Ključne reči: Modularni pristup, Diferencijalne jednačine, D’Alambertov princip, Hodni stroj, Opterećenja

1. UVODNA RAZMATRANJA

Opterećenja koja se razvijaju na hodnom stroju zglobnih mašina – točkaša utiču na performanse i pouzdanost svih elemenata mašine. Uprošćena šema za određivanje opterećenja na hodnom stroju dobija se kombinacijom diferencijalnih jednačina koje opisuju kretanje saglasno D’Alambertovim principom.

2. ODREĐIVANJE OPTEREĆENJA

Zglob buldozera (Slika 1) omogućava nezavisne ugaone hodove pogonskih i proizvodnih modula usled kotrljanja (osa Ox) i bočnog kretanja (osa Oy), kao i zajednički hod ovih modula usled podužnog nagiba (osa Oz).

Pretpostavimo da je:

- masa svakog zglobnog modula buldozera centrirana u prednjoj i zadnjoj vertikalnoj ravni;
- relativno kretanje radnog priključka i pogonskog modula jednako nuli u prenosnom režimu i u trenutku kada radni priključak stupa u interakciju sa zemljom.

Matematička simulacija pojave podužnog nagiba buldozera leži u činjenici da glavni vektor spoljnih sila mora biti u prednjoj i zadnjoj ravni, tj. $\sum F_{kz}^e = 0$ (Slika 1).

Rezultujući momenat spoljnih sila mora biti paralelan sa osom Oz , tj. $\sum M_x^e = 0$, $\sum M_y^e = 0$. Kada je $t_0 = 0$, onda je $\omega_o(0) = \omega_y(0) = 0$, $V_z(0) = 0$.

Gore pomenuti uslovi znače da pod uzdužnim nagibom buldozer vrši paralelno kretanje relativno u odnosu na ravan $A\xi_1\eta_1$ (Slika 1). Koordinatni sistem $O\xi\eta\zeta$ je postepeno pokretni referentni sistem, čije su ose paralelne sa fiksnim referentnim osama $A\xi_1\eta_1\zeta_1$. Sistem koordinata $O\xi\eta\zeta$ je kruto povezan sa nosačem.

Da bismo odredili opterećenja $R_{\mathcal{M}}$ i R_{TM} na hodnom stroju buldozera, polazimo od D’Alambertovog principa [1]. Saglasno njemu glavni vektor i rezultujući momenat inercijalnih sila predstavljeni su na slici, pri čemu se tačka O uzima kao

pol redukcije inercijalnih sila. Iz jednačina ravnoteže formiranih saglasno D’Alambertovom principu, sile reakcije staze po kojoj se kreće mašina se mogu dati u obliku:

$$\begin{aligned} R_{\mathcal{M}} = & \left[-F_1(l_1 + l_2)\cos\theta + P_1(l_2 + a_1)\cos\theta + \right. \\ & P_2(l_2 - a_2)\cos\theta - \Phi_\xi(b_0 + h_0 - \eta_0) - \Phi_\eta l_2 \cos\theta - \\ & M_0^\Phi + P_3(L_1 + l_2 + (l_c + s)\cos(\theta + \theta_3)) + \\ & \left. W_{KB}(L_1 + l_2 + (L_3 - s)\cos(\theta - \theta_3)) - W_{KT} \cdot \delta_k + M_{(OP)_B} \right] \\ & / (l_1 + l_2)\cos\theta, \end{aligned} \quad (1)$$

$$\begin{aligned} R_{TM} = & \left[-F_1(l_1 + l_2)\cos\theta + P_1(l_2 + a_1)\cos\theta + \right. \\ & P_2(l_2 - a_2)\cos\theta - \Phi_\xi(b_0 + h_0 - \eta_0) - \Phi_\eta l_2 \cos\theta - \\ & M_0^\Phi + P_3(L_1 + l_2 + (l_c + s)\cos(\theta + \theta_3)) + \\ & \left. W_{KB}(L_1 + l_2 + (L_3 - s)\cos(\theta - \theta_3)) - \right. \\ & \left. W_{KT} \cdot \delta_k + M_{(OP)_B} \right] / (l_1 + l_2)\cos\theta, \end{aligned} \quad (2)$$

Članovi u jednačinama (1) i (2) su:

$R_{\mathcal{M}}$ i R_{TM} - sile reakcije na pogonske i proizvodne module;

F_1 i F_2 - elastične sile istezanja i pritiska na delu pneumatika, tj.

$$F_1 = c(\eta_0 + l_1\theta),$$

$$F_2 = c(\eta_0 - l_2\theta),$$

c - vertikalna krutost pneumatika,

η_0 - izvijanje pola O usled podužnog nagiba;

Projekcije glavnog vektora inercijalnih sila na inercijalne ose date su izrazima:

$$\begin{aligned} F_\xi &= ma_{c\xi} = m(\ddot{\xi}_0 - (x_c \cos\theta - y_c \sin\theta) \cdot \dot{\theta}^2 - (x_c \sin\theta + y_c \cos\theta) \cdot \ddot{\theta}) \\ F_\eta &= ma_{c\eta} = m(\ddot{\eta}_0 - (x_c \sin\theta + y_c \cos\theta) \cdot \dot{\theta}^2 + (x_c \cos\theta - y_c \sin\theta) \cdot \ddot{\theta}) \end{aligned}$$

gde su:

$\ddot{\xi}_0$ i $\ddot{\eta}_0$ - komponente ubrzanja pola O ;

x_c i y_c - koordinate težišta masa buldozera u koordinatnom sistemu $Oxyz$ kruto povezanog sa nosačem:

$$x_c = (m_1 a_1 + m_2 a_2) / m; y_c = (m_1 b_1 + m_2 b_2) / m.$$

Ove koordinate u inercijalnom sistemu su

$$\begin{aligned} x_{\xi} &= x_c \cos \theta - y_c \sin \theta \\ y_{\eta} &= x_c \sin \theta + y_c \cos \theta \end{aligned}$$

Rezultujući moment inercijalnih sila jednak je $M_0^F = J_0 \ddot{\theta}$, gde je:

J_c - moment inercije buldozera u odnosu na osu koja prolazi kroz pol O pod pravim uglom u odnosu na prednju i zadnju ravan mašine;

m_1, m_2, m_3 - mase odgovarajućih pogonskih i proizvodnih modula i radnog priključka, pri čemu je ukupna masa $m = m_1 + m_2 + m_3$.

Parametri $\ddot{\xi}_0, \ddot{\eta}_0, \dot{\theta}$ i $\ddot{\theta}$ koji se javljaju u (1) i (2), mogu se odrediti na osnovu sistema diferencijalnih jednačina usled podužnih nagiba formiranih na osnovu uopštenog matematičkog modela zglobnih mašina [2] korišćenjem Lagrangeovih jednačina drugog reda.

Kinetička energija određena je slično metodi opisanoj u [3]. Potencijalna energija buldožera pod uzdužnim nagibom jednaka je

$$\begin{aligned} \Pi &= 2c\eta_0^2 + c(l_1^2 + l_2^2)\theta^2 + 2c(l_1 - l_2)\eta_0\theta + \\ &+ \frac{1}{2}c_{\rho_0}(\xi_0 \cos \theta + \eta_0 \sin \theta - s)^2 \end{aligned} \quad (3)$$

Sile vuče i sile otpora i na svakom točku uzete su kao u [4]:

$$T_{bi} = T_{oi} \left(1 - \frac{0,065}{V_n} \cdot \dot{x}_i - \frac{0,935}{V_n^5} \cdot \dot{x}_i^5 \right) \quad (4)$$

$$i = 1, 2$$

$$W_{fi} = R_i \cdot f \quad (5)$$

gde je:

T_0 - maksimalna vrednost vučne snage na spojnici;
 V_n - početna brzina buldozera u trenutku kada nož prodire u zemlju.

Otpor kopanja [4] može se definisati kao:

$$W_k = A_x x + C_x x^2 + D_x x^3 \quad (6)$$

gde su:

$$A_x = 25,28 \cdot \left(\frac{\rho_x}{\rho_1} \right) \cdot \left(\frac{\delta_{1x}}{\delta_1} \right) \cdot \left(\frac{B_x}{B_1} \right),$$

$$C_x = 0,664 \cdot A_x, D_x = 0,81 \cdot A_x;$$

Parametri koji opisuju iskapano tlo su:

ρ_l, B_l i ρ_x, B_x - konzistencija tla i širine kašike referentnog i ispitivanog noža,

δ_{lx} - debljina isečenog tla.

Diferencijalne jednačine formirane na osnovu generalizovanog matematičkog modela zglobnih mašina koje opisuju kretanje buldozera pod uzdužnim nagibom date su u sledećem obliku:

$$\begin{aligned} m\ddot{\xi}_0 - (B \cos \theta + A \sin \theta)\ddot{\theta} + (B \sin \theta - A \cos \theta)\dot{\theta}^2 = \\ T_1 + T_2 - W_{f1} - W_{f2} - W_{kr}, \end{aligned}$$

$$\begin{aligned} m\ddot{\eta}_0 - (B \sin \theta - A \cos \theta)\ddot{\theta} - (B \cos \theta + A \sin \theta)\dot{\theta}^2 = \\ -4c\eta_0 + 2c(l_2 - l_1) - W_{kb}, \end{aligned}$$

$$-(B \cos \theta + A \sin \theta)\ddot{\xi}_0 - (B \sin \theta - A \cos \theta)\ddot{\eta}_0 + J_0\ddot{\theta} =$$

$$= 2c(l_2 - l_1)\eta_0 - 2c(l_2^2 + l_1^2)\theta + W_{kb}l_3 + W_{kr}l_3 +$$

$$(W_{kr} - T_1 - T_2 + W_{f1} + W_{f2})(H - \eta_0),$$

(7)

Koeficijenti A i B predstavljaju ukupne statičke momente modula buldozera.

Jednačine (1) i (2) zajedno sa sistemom diferencijalnih jednačina (7) određuju opterećenja na hodnom stroju buldozera usled podužnog nagiba. Slika 2 prikazuje grafike opsega varijacije opterećenja pogonskih i proizvodnih modula.

3. ANALIZA REZULTATA

Uparednom analizom grafika a) i b), a u trenutku ubrzanja, koje traje oko 2 sek., uočava se da opterećenja dostižu svoje maksimalne vrednosti. Ona se povećavaju sa rastom vrednosti vertikalne komponente a opseg varijacije opterećenja se menja saglasno:

- $W_{KB} = 0,6 \cdot W_{KT}$;
80 < R_{PM} < 190 i 30 < R_{EM} < 80;
- $W_{KB} = 1,2 \cdot W_{KT}$;
120 < R_{PM} < 290 i 50 < R_{EM} < 120;
- $W_{KB} = 2,6 \cdot W_{KT}$;
140 < R_{PM} < 500 i 60 < R_{EM} < 270.

Opseg varijacija opterećenja na pogonskom modulu je 30 < R_{EM} < 270, a na proizvodnom 80 < R_{PM} < 500. Učestalost vibracija opterećenja na pogonskom modulu je skoro četiri puta veća od frekvencije vibracija opterećenja na proizvodnom modulu. Način na koji se krive R_{PM} , R_{EM} menjaju sprečava preklapanje nekoliko vibracija različitih frekvencija; pogonski i tehnološki moduli vibriraju u antifazi.

Slika 1. Šematski prikaz sila koje deluju na buldožer u režimu rada

Slika 2. Dinamika opsega promene opterećenja na hodnom stroju buldožera (2-EM; 1-PM) pri različitim korelacijama horizontalnih i vertikalnih sila otpora kopanju:

a) $W_K = 0.6 \cdot W_{KG}$ б) $W_{KB} = 1.2 \cdot W_{kg}$ в) $W_{KB} = 2.6 \cdot W_{KT}$

3. ZAKLJUČAK

1. Formiran je matematički model buldozera koji omogućava određivanje opterećenja na njegovom donjem delu usled podužnog nagiba.
2. Dokazan je uticaj vertikalne komponente sile otpora kopanja na rast opterećenja na pogonskim i proizvodnim modulima.
3. Opterećenja na pogonskom modulu su dvostruka, dva i po puta veća od opterećenja na proizvodnom modulu.
4. Generalizovani model, diferencijalne jednačine, D’Alambertov princip mogu se koristiti prilikom određivanja opterećenja na hodnom stroju različitih tehnoloških mašina ne samo usled podužnog nagiba već i tokom njihovog kotrljanja i bočnog pomeranja.

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Evaluating the Loads on Bulldozer Undercarriage Under Longitudinal Trim

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Based on the air-wheel type machines simulation, a bulldozer mathematic model for all its operating modes has been worked out. Evaluation of loads on the bulldozer undercarriage under longitudinal trim has been considered as an example of possible implementing the potential of the mathematical model proposed.

Keywords: *Modular approach, Differential equations, D'Alambert's principle, Undercarriage, Loads.*

1. INTRODUCTION

Loads that develop on the undercarriage of articulated air-wheel type machines influence all machine elements' performance and reliability. Formalized scheme for evaluating the loads on the undercarriage is in a combination of differential equations that describe machine motion with D'Alambert's principle.

2. EVALUATING THE LOADS

Bulldozer joint (Fig.1) ensuring independent angular travels of the power and production modules correspondingly under roll (axle Ox) and lateral movement (axle Oy) as well as cooperative travels of these modules under longitudinal trim (axle Oz).

Let us assume that:

- the mass of each articulated bulldozer module is centered in the vertical fore-and-aft plane;
- under the conveying mode, and when the working attachment interacts with the ground, the relative movement of both the working attachment and the power module equals zero.

The bulldozer longitudinal trim phenomenon's mathematic simulation lies in the fact that the primary vector of external forces must be in the fore-and-aft plane, i.e. $\sum F_{k_z}^e = 0$ (Fig.1). The resultant moment of the external forces must be parallel to axle Oz , i.e. $\sum M_x^e = 0, \sum M_y^e = 0$.

When $t_0 = 0$ then $\omega_o(0) = \omega_y(0) = 0, V_z(0) = 0$ takes place.

The conditions mentioned above mean that the bulldozer makes a plane-parallel motion relative to the plane $A\xi_1\eta_1$ (Fig.1). The coordinates system $O\xi\eta\zeta$ is a progressively moving reference system whose axes are parallel to $A\xi_1\eta_1\zeta_1$ fixed reference axes. The system of coordinates $O\xi\eta\zeta$ is rigidly connected with the carrier.

To evaluate loads $R_{\mathcal{M}}$ and R_{TM} on the bulldozer undercarriage, we shall refer to D'Alambert's principle

[1]. In compliance with it, the primary vector and the resultant moment of inertial forces are represented in the figure, with point O being taken as the pole of inertial forces reduction.

From equilibrium equations made by D'Alambert's principle, the roadway reacting forces are of the form:

$$R_{\mathcal{M}} = \left[-F_1(l_1 + l_2)\cos\theta + P_1(l_2 + a_1)\cos\theta + P_2(l_2 - a_2)\cos\theta - \Phi_\xi(b_0 + h_0 - \eta_0) - \Phi_\eta l_2 \cos\theta - M_0^\phi + P_3(L_1 + l_2 + (l_c + s)\cos(\theta + \theta_3)) + W_{KB}(L_1 + l_2 + (L_3 - s)\cos(\theta - \theta_3)) - W_{KR} \cdot \delta_k + M_{(OP)_B} \right] / (l_1 + l_2) \cos\theta,$$

$$R_{TM} = \left[-F_1(l_1 + l_2)\cos\theta + P_1(l_2 + a_1)\cos\theta + P_2(l_2 - a_2)\cos\theta - \Phi_\xi(b_0 + h_0 - \eta_0) - \Phi_\eta l_2 \cos\theta - M_0^\phi + P_3(L_1 + l_2 + (l_c + s)\cos(\theta + \theta_3)) + W_{KB}(L_1 + l_2 + (L_3 - s)\cos(\theta - \theta_3)) - W_{KR} \cdot \delta_k + M_{(OP)_B} \right] / (l_1 + l_2) \cos\theta,$$

In equations (1) and (2) are:

$R_{\mathcal{M}}$ and R_{TM} - reacting forces on the power and production modules;

F_1 and F_2 - elastic flexible up and down pull on the part of a pneumatic tire, i.e.

$$F_1 = c(\eta_0 + l_1\theta),$$

$$F_2 = c(\eta_0 - l_2\theta),$$

c - vertical rigidity of pneumatic tire,

η_0 - camber of pole O under longitudinal trim;

Projections of the primary vector of inertial forces on to inertial axes equal:

$$F_\xi = ma_{c\xi} = m(\ddot{\xi}_0 - (x_c \cos\theta - y_c \sin\theta) \cdot \dot{\theta}^2 - (x_c \sin\theta + y_c \cos\theta) \cdot \ddot{\theta})$$

$$F_\eta = ma_{c\eta} = m(\ddot{\eta}_0 - (x_c \sin\theta + y_c \cos\theta) \cdot \dot{\theta}^2 + (x_c \cos\theta - y_c \sin\theta) \cdot \ddot{\theta})$$

where are:

$\ddot{\xi}_o$ and $\ddot{\eta}_o$ – pole O acceleration components;

x_c and y_c – coordinates of bulldozer masses center in the system of coordinates $Oxyz$ rigidly connected with the carrier:

$$x_c = (m_1 a_1 + m_2 a_2) / m; y_c = (m_1 b_1 + m_2 b_2) / m.$$

These coordinates will be written in the inertial system as:

$$x_{\xi'} = x_c \cos \theta - y_c \sin \theta$$

$$y_{\eta'} = x_c \sin \theta + y_c \cos \theta$$

The resultant moment of inertial forces equals $M_0^F = J_0 \ddot{\theta}$, where is:

J_c – bulldozer inertia moment relative to the axis passing through pole O at a right angle to the machine's fore-and-aft plane;

m_1, m_2, m_3 – masses of correspondingly power and production modules, working attachment, and total mass $m = m_1 + m_2 + m_3$.

Parameters $\ddot{\xi}_o, \ddot{\eta}_o, \dot{\theta}$ and $\ddot{\theta}$ that occur in (1) and (2) can be determined from the get from longitudinal trim differential equation system composed based on the generalized mathematical model of articulated machines [2] using Lagrange's equations of the second genre.

The kinetic energy was determined similarly to the method described in [3]. The bulldozer potential energy under longitudinal trim is equal to

$$\begin{aligned} \Pi = & 2c\eta_0^2 + c(l_1^2 + l_2^2)\theta^2 + 2c(l_1 - l_2)\eta_0\theta + \\ & + \frac{1}{2}c_{po}(\xi_0 \cos \theta + \eta_0 \sin \theta - s)^2 \end{aligned} \quad (3)$$

Traction forces T_1 and T_2 , resistance forces W_{f_1} and W_{f_2} on each wheel were taken as in [4]:

$$T_{bi} = T_{oi} \left(1 - \frac{0,065}{V_n} \cdot \dot{x}_i - \frac{0,935}{V_n^5} \cdot \dot{x}_i^5 \right) \quad (4)$$

$$i = 1, 2$$

$$W_{f_i} = R_i \cdot f \quad (5)$$

where is:

T_0 – the maximum value of tractive power on coupling;
 V_n – the initial bulldozer speed at the moment when the blade penetrates the ground.

Digging strength as in [4]:

$$W_k = A_x x + C_x x^2 + D_x x^3 \quad (6)$$

where are:

$$A_x = 25,28 \cdot \left(\frac{\rho_x}{\rho_l} \right) \cdot \left(\frac{\delta_{lx}}{\delta_l} \right) \cdot \left(\frac{B_x}{B_l} \right),$$

$$C_x = 0,664 \cdot A_x, D_x = 0,81 \cdot A_x;$$

Parameters that describe the developed ground are:

ρ_l, B_l and ρ_x, B_x – ground consistency, and widths of scoops of the reference blade and the tested one;

δ_{lx} – the thickness of the cut-out ground.

The differential equations made based on the generalized mathematical model of articulated machines and describing the bulldozer motion under longitudinal trim are in the following form:

$$m\ddot{\xi}_0 - (B \cos \theta + A \sin \theta)\ddot{\theta} + (B \sin \theta - A \cos \theta)\dot{\theta}^2 =$$

$$T_1 + T_2 - W_{f_1} - W_{f_2} - W_{kr}$$

$$m\ddot{\eta}_0 - (B \sin \theta - A \cos \theta)\ddot{\theta} - (B \cos \theta + A \sin \theta)\dot{\theta}^2 =$$

$$-4c\eta_0 + 2c(l_2 - l_1) - W_{kb}$$

$$- (B \cos \theta + A \sin \theta)\ddot{\xi}_0 - (B \sin \theta - A \cos \theta)\ddot{\eta}_0 + J_0 \ddot{\theta} =$$

$$= 2c(l_2 - l_1)\eta_0 - 2c(l_2^2 + l_1^2)\theta + W_{kb}l_3 + W_{kr}l_3 +$$

$$(W_{kr} - T_1 - T_2 + W_{f_1} + W_{f_2})(H - \eta_0)$$

(7)

Coefficients A and B present the total of the static moments of bulldozer modules.

Equations (1) and (2) together with the differential equation system (7) evaluate loads on the bulldozer undercarriage under its longitudinal trim.

Fig. 2 shows the graphs of the load variation range on the power and production modules.

3. THE ANALYSIS OF RESULTS

As it follows from the comparison of graphs a) and b), at the moment of speeding-up, which lasts for about 2 sec., loads reach their extreme values. They increase with the growth of the vertical component value; the load variation range increases:

- at $W_{kb} = 0,6 \cdot W_{kr}$;
 $80 < R_{PM} < 190$, and $30 < R_{EM} < 80$;
- at $W_{kb} = 1,2 \cdot W_{kr}$;
 $120 < R_{PM} < 290$, and $50 < R_{EM} < 120$;
- at $W_{kb} = 2,6 \cdot W_{kr}$;
 $140 < R_{PM} < 500$, and $60 < R_{EM} < 270$.

The variation range of loads on the power module makes up $30 < R_{EM} < 270$, and on production one $80 < R_{PM} < 500$. The vibration frequency of loads on the power module is nearly four times as high as the vibration frequency of loads on the production module. The way curves R_{PM} , and R_{EM} change proves the overlapping of several vibrations of various frequencies; power and technological modules vibrate in antiphase.

Figure 1. Schematic view of forces affecting the bulldozer in the operating mode

Figure 2. Dynamics of the load variation range on the bulldozer undercarriage (2-EM; 1-PM) at various correlations of horizontal and vertical forces of resistance to digging:

a) $W_K = 0.6 \cdot W_{KG}$ b) $W_{KB} = 1.2 \cdot W_{KG}$ c) $W_{KB} = 2.6 \cdot W_{KT}$

4. CONCLUSION

1. The mathematical model that allows evaluating loads on bulldozer undercarriage under longitudinal trim has been formed.
2. The influence of digging resisting force vertical component on loads' growth on the power and production modules has been proved.
3. Loads on the power module are twofold, two and a half times as high as those on the production module.
4. The generalized model, differential equations, D'Alembert's principle – can be used while evaluating loads on the undercarriage of various technological machines under longitudinal trim and during their rolling and lateral movement.

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