Kompjutersko modeliranje zone kopanja bagera sa kašikom

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U radu su prikazani tehnika, algoritam i kompjuterski programi u sistemu Mathcad namenjeni za definisanje radne zone kopanja bagera sa kašikom. Radna zona kopanja zemljišta uključuje niz položaja elemenata radnog uređaja. Svaki položaj prikazan je odgovarajućim programom i grafičkim prikazom u Mathcad-u. Ponuđen algoritam proračuna i grafičke interpretacije položaja radne zone bagera sa kašikom pruža mogućnost smanjenja vremena i rada u takvim analizama, a osim toga povezuje posmatrana istraživanja kada je u pitanju promena parametara elemenata radne opreme.

Ključne reči: zona kopanja, bager sa kašikom, tehnika, kompjuterski program

0. UVOD

Jedna od najvažnijih karakteristika bagera sa kašikom je radna zona, koja zavisi od vrste opreme, položaja radnog uređaja, geometrije elemenata radnog uređaja i ugla njihovog obrtanja. Razmotrićemo kao primer modeliranje radne zone bagera sa dubinskom kašikom, sl. 1. Ova radna zona se sastoji od nekoliko delova (krivih): (0 - 1); (1 - 2); (2 - 3); (3 - 4); (4 - 5); (5 - 6); (6 - 7) (7 - 0). Svaki od delova zone kopanja ima svoj poluprečnik, ugao obrtanja i centar.

Konstruisanje zone kopanja je veoma kompleksan zadatak. Može se izvesti grafički ili analitički. Na sl. 1 dat je primer radne zone bagera sa elementima radnog uređaja.

Sl. 1. Primer radne zone bagera sa dubinskom kašikom

1. KINEMATSKA ANALIZA

Radna zona kopanja bagera predstavlja određeni niz povezanih položaja. Za svaki položaj poznati su veličine uglova obrtanja svih elemenata radnog uređaja (strele, držača kašike i kašike). Radna zona bagera obuhvata sledeće delove:

- *prvi deo* (0 - 1) – nastaje obrtanjem kašike za maksimalni ugao (α_{3max}), gde se vrh zuba kašike kreće od tačke 0, do tačke 1 koja leži na liniji koja prolazi kroz osu obrtanja strele i osu obrtanja kašike. Pri tome uglovi obrtanja strele (α_{1max}) i držača kašike (α_{2max}) su nepromenljivi;
- *drugi deo* (1 - 2) – nastaje obrtanjem samo strele od maksimalnog ugla okretanja (α_{1max}) do minimalnog ugla okretanja (α_{1min}) sa najvišim položajem kašike. Pri tome uglovi okretanja držača kašike i kašike se ne menjaju;
- *treći deo* (2 - 3) – nastaje samo obrtanjem kašike od tačke 2, do tačke 3. Vrh zuba kašike se kreće od tačke 2, do tačke 3 koja leži na liniji koja prolazi kroz osu držača kašike i osu okretanja kašike. Ugao obrtanja kašike je ϕ (sl. 4). Pri tome uglovi obrtanja držača kašike i kašike se ne menjaju;
- *četvrti deo* (3 - 4) – nastaje obrtanjem samo držača kašike od maksimalnog ugla okretanja (α_{2max}) do minimalnog (α_{2min}) sa maksimalnim položajem gde se vrh zuba kašike kreće od tačke 3 do tačke 4. Pri tome uglovi okretanja strele i kašike se ne menjaju;
- *peti deo* (4 - 5) – nastaje obrtanjem strele sa promenom ugla okretanja strele od minimalnog (α_{2min}) maksimalno mogućeg (α_{2max}). Vrh zuba kašike se kreće od tačke 4 do tačke 5. Pri tome uglovi okretanja držača kašike i kašike se ne menjaju;
- *šesti deo* (5 - 6) – nastaje obrtanjem kašike i to promenom ugla oobrtanja od prethodnog položaja do minimalno mogućeg (α_{3min}). Vrh zuba kašike se kreće od tačke 0 do tačke 1. Pri tome uglovi okretanja strele i držača kašike se ne menjaju;
- *sedmi deo* (6 - 7) – nastaje obrtanjem samo držača kašike od maksimalnog ugla okretanja (α_{2max}) do minimalno mogućeg (α_{2min}).

Vrh zuba kašike se kreće od tačke 6 do tačke 7. Pri tome uglovi obrtanja strele i kašike se ne menjaju;

- *osmi deo* (7 - 0) – nastaje obrtanjem kašike od minimalno mogućeg ugla (α_{3min}) do maksimalnog ugla obrtanja (α_{3max}). Pri tome uglovi okretanja strele i držača kašike se ne menjaju;

Kao pravilo, radi pojednostavljenja, opis svakog elementa mašine i mehanizama sprovedeno je u lokalnom koordinatnom sistemu koji odgovara projektovanom ili razmatranom elementu (strele, držač kašike i kašika). Međutim, za određivanje detaljnijih karakteristika međusobno povezanih elemenata potrebno je razmatranje u osnovnom koordinatnom sistemu.

2. MODELIRANJE RADNE ZONE KOPANJA

Modeliranje radne zone kopanja uključuje:

- formiranje matrice transformacije iz lokalnog koordinatnog sistema kašike u lokalni sistem držača kašike;
- formiranje matrice transformacije iz lokalnog sistema držača kašike u lokalni sistem strele;
- formiranje matrice transformacije iz lokalnog sistema strele u osnovni sistem koordinata bagera;
- određivanje vrednosti uglova nagiba strele, držača kašike i kašike u radnom opsegu;
- uzastopno određivanje koordinata za svaki položaj u radnoj zoni korišćenjem razvijenog algoritma i grafička prezentacija rezultata proračuna.

3. FORMIRANJE MATRICE TRANSFORMACIJE IZ JEDNOG U DRUGI KOORDINATNI SISTEM

Osnovni koordinatni sistem bagera $0_0X_0Y_0$ – je sistem kombinovan sa površinom podloge i osom rotacije obrtne platforme.

Radni uređaj bagera sa kašikom ima tri stepena slobode. Svaki element radnog uređaja (strele, držač kašike i kašika) je definisan sa tri uglovne koordinate: α_1 – ugao obrtanja strele, α_2 – ugao obrtanja držača kašike i α_3 – ugao obrtanja kašike. Predpostavićemo, da je pozitivna vrednost uglovni koordinata okretanja svakog sistema odgovara suprotnom smeru kazaljke na satu.

Svaki element radnog uređaja ima lokalni sistem: strele – $0_1X_1Y_1$; držač kašike – $0_2X_2Y_2$; kašika – $0_3X_3Y_3$. Početak lokalnog sistema bira se na spoju elemenata radnog uređaja. Koordinate svake tačke nekog elementa radnog uređaja lakše se određuju u lokalnom sistemu.

Razmotrimo na početku transformacije koordinata tačke iz lokalnog sistema strele u osnovni sistem koordinata bagera.

Na sl. 2 dati su osnovni sistem koordinata bagera $0_0X_0Y_0$ i lokalni sistem koordinata strele $0_1X_1Y_1$.

Sl. 2. Povezivanje dve susedne koordinate

Pretpostavimo, da su koordinate tačke $T(X_{1T}, Y_{1T})$ u lokalnom sistemu koordinata strele $0_1X_1Y_1$ poznate. To je neophodno za definisanje koordinata ove tačke u osnovnom sistemu $0_0X_0Y_0$ – sistem koordinata bagera.

Koordinate tačke T na osi X_1 u sistemu $0_0X_0Y_0$ mogu biti definisane, korišćenjem pravouglog trougla $0_1d_4d_5$ i d_1d_5T ,

$$X_{0T} = O_1d_4 - d_3d_4 + a_1 = O_1d_4 - d_1d_5 + a_1, \quad (1)$$

gde je: O_1d_4 – stranica trougla $0_1d_4d_5$;

d_1d_5 – stranica trougla d_1d_5T ;

a_1 – koordinata početka sistema $0_1X_1Y_1$ na osi X_0 sistema $0_0X_0Y_0$.

Poznavajući vrednost ugla obrtanja α_1 u sistemu $0_1X_1Y_1$ razmatrajući osu X_0 sistema $0_0X_0Y_0$, moguće je pronaći stranicu trougla 0_1d_4 iz trougla $0_1d_4d_5$.

$$O_1d_4 = X_{1T} \cdot \cos(\alpha_1). \quad (2)$$

Moguće je pronaći stranicu trougla d_1d_5 iz trougla d_1d_5T

$$d_1d_5 = Y_{1T} \cdot \sin(\alpha_1). \quad (3)$$

Zamenom izraza (2) i (3) u (1), dobija se izraz za X_{0T}

$$X_{0T} = X_{1T} \cdot \cos(\alpha_1) - Y_{1T} \cdot \sin(\alpha_1) + a_1. \quad (4)$$

Koordinate tačke T na osi Y_0 u sistemu $0_0X_0Y_0$ mogu se odrediti, korišćenjem stranica trouglova $0_1d_4d_5$ i d_1d_5T ,

$$Y_{0T} = d_1d_3 + Td_1 + b_1 = d_4d_5 + Td_1 + b_1, \quad (5)$$

gde je: d_4d_5 – stranica trougla $0_1d_4d_5$;

Td_1 – stranica trougla d_1d_5T ;

b_1 – koordinate početka sistema $0_1X_1Y_1$ na osi Y_0 sistema $0_0X_0Y_0$.

Poznavajući vrednost ugla okretanja moguće je pronaći stranicu trougla d_4d_5 iz trougla $0_1d_4d_5$.

$$d_4d_5 = X_{1T} \cdot \sin(\alpha_1). \quad (6)$$

Slično, moguće je pronaći stranicu trougla Td_1 iz trougla d_1d_5T

$$Td_1 = Y_{1T} \cdot \cos(\alpha_1). \quad (7)$$

Zamenom (6) i (7) u (5), dobija se izraz za Y_{0T}

$$Y_{0T} = X_{1T} \cdot \sin(\alpha_1) + Y_{1T} \cdot \cos(\alpha_1) + b_1. \quad (8)$$

Za modeliranje kretanja radnog uređaja bagera – kašike u prostoru iskoristićemo prednost matematičkog alata zasnovanog na predstavljanju ulaznih i izlaznih podataka u formi vektora kolona i matrica transformacije reda 4×4. Nakon toga, gore navedenu transformaciju koordinata pomeranja je moguće prikazati u matričnom obliku

$$T = \begin{bmatrix} x_{0T} \\ y_{0T} \\ z_{0T} \\ 1 \end{bmatrix} = \begin{bmatrix} \cos(\alpha_1) & -\sin(\alpha_1) & 0 & a1 \\ \sin(\alpha_1) & +\cos(\alpha_1) & 0 & b1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_{1T} \\ y_{1T} \\ z_{1T} \\ 1 \end{bmatrix} = \begin{bmatrix} x_{1T} \cdot \cos(\alpha_1) - y_{1T} \cdot \sin(\alpha_1) + a1 \\ x_{1T} \cdot \sin(\alpha_1) + y_{1T} \cdot \cos(\alpha_1) + b1 \\ z_{1T} \\ 1 \end{bmatrix} \quad (9)$$

4. DEFINISANJE UGLA OBRTANJA KAŠIKE

U narednom delu definišaću se ugao obrtanja kašike u prvom delu putanje kopanja - (0-1). Na sl. 3 data je šema položaja elemenata radnog uređaja bagera za definisanje ugla obrtanja kašike na prvom delu putanje (0-1). Obrtanje kašike u prvom delu ide od $(\alpha_{3max} - \varphi)$ a za gornji ugao nagiba strele α_{1max} i držača kašike α_{2max} do linije koja prolazi kroz osu okretanja strele - O_1 i osu okretanja kašike - O_3 , obezbeđujući maksimalni početni položaj kašike.

Sl. 3. Šema položaja elemenata radnog uređaja bagera za definisanje ugla obrtanja kašike na prvom delu putanje (0-1)

Korišćenjem položaja radnog uređaja sa što više podignutim: strelom, držačem kašike i kašikom (sl.3), odredićemo:

- koordinate centra obrtanja kašike $O_3(X_3, Y_3)$ u lokalnom sistemu kašike $O_1X_1Y_1$:

$$X_3 = O_1B + BX_3 = L_1 \cdot \cos(\alpha_{1max}) + L_2 \cdot \cos(\alpha_{1max} + \alpha_{2max}); \quad (9)$$

$$Y_3 = O_1A + AY_3 = L_1 \cdot \sin(\alpha_{1max}) + L_2 \cdot \sin(\alpha_{1max} + \alpha_{2max}); \quad (10)$$

- koordinate centra obrtanja kašike $O_3(X_3, Y_3)$ u osnovnom sistemu $O_0X_0Y_0$:

$$X1_3 = X_3 + a1; \quad (11)$$

$$Y1_3 = Y_3 + b1; \quad (12)$$

- rastojanje od ose strele do ose kašike L_{pc} , m

$$L_{12} = \sqrt{X_3^2 + Y_3^2}, \quad (13)$$

- ugao okretanja strele β_{01} za položaj (0 - 1) biće određen iz trougla $O_1O_2O_3$ sl 3, korišćenjem kosinusne teoreme.

$$L_1^2 = L_2^2 + L_{12}^2 - 2 \cdot L_2 \cdot L_{12} \cdot \cos(\varphi); \quad (14)$$

$$\varphi = \arccos\left(\frac{L_2^2 + L_{12}^2 - L_1^2}{2 \cdot L_2 \cdot L_{12}}\right); \quad (15)$$

$$\beta_{01} = \alpha_{3max} - \varphi. \quad (16)$$

Nakon toga, definišaćemo ugao obrtanja kašike na drugom delu radne putanje bagera - (2-3).

Na sl. 4 data je šema položaja elemenata radnog uređaja bagera za definisanje dela putanje (2-3), obrtanjem kašike od ugla 0 do $(-\varphi)$ i to za položaje strele određen uglom α_{1min} i držača kašike određenog uglom α_{2max} .

Na sl. 4 data je šema položaja elemenata radnog uređaja za definisanje ugla obrtanja kašike na trećem delu putanje (2-3). Kašika se obrće na trećem delu putanje od ugla $(-\varphi)$ za položaj strele pod uglom α_{1min} i držača pod uglom α_{2max} do linije koja prolazi kroz osu obrtanja držača - O_2 i osu obrtanja kašike - O_3 , obezbeđujući maksimalni položaj kašike na delu putanje (3-4) pri obrtanju držača.

Sl. 4. Šema položaja elemenata radnog uređaja bagera za definisanje ugla obrtanja kašike na trećem delu putanje radne zone (2-3)

5. KOMPJUTERSKO MODELIRANJE RADNE ZONE

Algoritam za kompjutersko modeliranje radne zone bagera sa radnim uređajem povratne kašike korišćenjem Mathcada, prikazan je u narednim redovima.

Ulazni podaci:

- max i min uglovi obrtanja strele u X_0Y_0 ravni, (°):

$$\alpha_{1\max}=50^\circ; \alpha_{1\min}=-60^\circ$$

- rastojanje između ose obrtne platforme i ose strele, (m):
 $a_1=0.2$

- rastojanje između podloge i ose okretanja strele, (m):
 $b_1=2.0$

- max i min uglovi obrtanja držača u X_1Y_1 ravni, (°):

$$\alpha_{2\max}=-20^\circ; \alpha_{2\min}=-180^\circ$$

- kinematic length of a boom, (m): $L_1=6.5$

- max and min turning angles of bucket arm in X_2Y_2 plane, (°): $\alpha_{3\max}=30^\circ; \alpha_{3\min}=-120^\circ$

- kinematska dužina držača, (m): $L_2=3.2$

- kinematska dužina kašike, (m): $L_3=1.64$

- vektor koordinata zuba kašike u lokalnom sistemu kašike $O_3X_3Y_3$, (m)

$$TZ := (L_3 \ 0 \ 0 \ 1)^T$$

Procedura proračuna

1. Koraci promene ugla nagiba strele $\Delta\alpha_1$, držača kašike $\Delta\alpha_2$ i kašike $\Delta\alpha_3$, radian

$$\Delta\alpha_1 := \frac{\alpha_{1\max} - \alpha_{1\min}}{N}$$

$$\Delta\alpha_2 := \frac{\alpha_{2\max} - \alpha_{2\min}}{N}$$

$$\Delta\alpha_3 := \frac{\alpha_{3\max} - \alpha_{3\min}}{N}$$

2. Proračun matrice transformacije $M32(\alpha_3)$ koordinata kašike O_3, X_3, Y_3 u koordinate držača kašike O_2, X_2, Y_2 i matrice transformacije $M21(\alpha_2)$ koordinata držača O_2, X_2, Y_2 u koordinate strele O_1, X_1, Y_1

$$M32(\alpha_3) := \begin{pmatrix} \cos(\alpha_3) & -\sin(\alpha_3) & 0 & L_2 \\ \sin(\alpha_3) & \cos(\alpha_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$M21(\alpha_2) := \begin{pmatrix} \cos(\alpha_2) & -\sin(\alpha_2) & 0 & L_1 \\ \sin(\alpha_2) & \cos(\alpha_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

3. Proračun matrice transformacije $M10(\alpha_1)$ koordinata strele O_1, X_1, Y_1 u glavne koordinate bagera O_0, X_0, Y_0

$$M10(\alpha_1) := \begin{pmatrix} \cos(\alpha_1) & -\sin(\alpha_1) & 0 & a_1 \\ \sin(\alpha_1) & \cos(\alpha_1) & 0 & b_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

4. Koordinate centra obrtanja kašike O_3 na delu (0-1)

$$X_{31} := L_1 \cdot \cos(\alpha_{1\max}) + L_2 \cdot \cos(\alpha_{1\max} + \alpha_{2\max}) + a_1 = 7.149$$

$$Y_{31} := L_1 \cdot \sin(\alpha_{1\max}) + L_2 \cdot \sin(\alpha_{1\max} + \alpha_{2\max}) + b_1 = 8.579$$

5. Rastojanje od ose strele do ose držača kašike L_{12} , m

$$L_{12} := \sqrt{(X_{31} - a_1)^2 + (Y_{31} - b_1)^2} = 9.57$$

6. Veličina ugla obrtanja kašike na delu (0-1), rad., korišćenjem kosinusne teoreme

$$\varphi := \arccos\left(\frac{L_2^2 + L_{12}^2 - L_1^2}{2 \cdot L_2 \cdot L_{12}}\right) = 0.234$$

$$\beta_{01} := \alpha_{3\max} - \varphi = 0.289$$

7. Program proračuna grafika na delu putanje (0-1) radne zone bagera: obrtanje kašike od $\alpha_{3\max}$ do β_{01} ; za položaje držača određenog uglom $\alpha_{2\max}$; a strele uglom $\alpha_{1\max}$, radian

```

T01 := for j ∈ 0..N
    α3j ← α3max - j · Δα3
    α3j ← α3j if α3j > β01
    α3j ← β01 if α3j < β01
    T2 ← M32(α3j) · TZ
    T1 ← M21(α2max) · T2
    T ← M10(α1max) · T1
    Xj ← T0
    Yj ← T1
    T01 ← (Xj, Yj)

```

Grafik dela (0-1) radne zone bagera

8. Program proračuna i crtanja grafika na delu (0-1-2) radne zone bagera: obrtanje strele od α_{1max} do α_{1min} ; držač kašike pod uglom α_{2max} ; kašika pod uglom β_{01} , radian

```

T12 := | T2 ← M32( $\beta_{01}$ ) · TZ
        | T1 ← M21( $\alpha_{2max}$ ) · T2
        | for j ∈ 0..N
        |   |  $\alpha_{1j}$  ←  $\alpha_{1max} - j \cdot \Delta\alpha_1$ 
        |   | T ← M10( $\alpha_{1j}$ ) · T1
        |   |  $X_j$  ←  $T_0$ 
        |   |  $Y_j$  ←  $T_1$ 
        |   | T12 ←  $\begin{pmatrix} X \\ Y \end{pmatrix}$ 

```

Grafik dela (0-1-2) radne zone bagera

9. Program proračuna na delu (2-3) i crtanja grafika na delu (0-1-2-3) radne zone bagera: okretanje kašike od ugla 0 do β_{23} ; za držač kašike pod uglom α_{2max} ; a strela pod uglom α_{1min} , radian

```

 $\beta_{23} := -\varphi = -0.234$ 
T23 := | for j ∈ 0..N
        |   |  $\alpha_{3j}$  ←  $\beta_{01} - j \cdot \Delta\alpha_3$ 
        |   |  $\alpha_{3j}$  ←  $\alpha_{3j}$  if  $\alpha_{3j} > \beta_{23}$ 
        |   |  $\alpha_{3j}$  ←  $\beta_{23}$  if  $\alpha_{3j} < \beta_{23}$ 
        |   | T2 ← M32( $\alpha_{3j}$ ) · TZ
        |   | T1 ← M21( $\alpha_{2max}$ ) · T2
        |   | T ← M10( $\alpha_{1min}$ ) · T1
        |   |  $X_j$  ←  $T_0$ 
        |   |  $Y_j$  ←  $T_1$ 
        |   | T23 ←  $\begin{pmatrix} X \\ Y \end{pmatrix}$ 

```

Grafik dela (0-1-2-3) radne zone bagera

10. Program proračuna na delu (3-4) i crtanja grafika na delu (0-1-2-3-4) radne zone bagera: strela pod uglom α_{1min} ; za okretanje držača od ugla α_{2max} do α_{2min} ; a kašika pod uglom 0

```

T34 := | for j ∈ 0..N
        |   |  $\alpha_{2j}$  ←  $\alpha_{2max} - j \cdot \Delta\alpha_2$ 
        |   | T2 ← M32( $\beta_{23}$ ) · TZ
        |   | T1 ← M21( $\alpha_{2j}$ ) · T2
        |   | T ← M10( $\alpha_{1min}$ ) · T1
        |   |  $X_j$  ←  $T_0$ 
        |   |  $Y_j$  ←  $T_1$ 
        |   | T34 ←  $\begin{pmatrix} X \\ Y \end{pmatrix}$ 

```

Grafik dela (0-1-2-3-4) radne zone bagera

11. Program proračuna na delu (4-5) i crtanja grafika na delu (0-1-2-3-4-5) radne zone bagera: obrtanje strele od ugla α_{1min} do α_{1max} ; za držač pod uglom α_{2min} ; i kašika pod uglom 0

```

T45 := for j ∈ 0..N
      | α1j ← α1min + j · Δα1
      | T2 ← M32(β23) · TZ
      | T1 ← M21(α2min) · T2
      | T ← M10(α1j) · T1
      | Xj ← T0
      | Yj ← T1
      | T45 ← (Xj, Yj)

```

Grafik dela (0-1-2-3-4-5) radne zone bagera

12. Program proračuna na delu (5-6) i crtanja grafika na delu (0-1-2-3-4-5-6) radne zone bagera: strela pod uglom α_{1max} ; držač kašike pod uglom α_{2min} ; za okretanje kašike od 0 do α_{3min} .

```

T56 := for j ∈ 0..N
      | α3j ← β23 - j · Δα3
      | α3j ← α3j if α3j > α3min
      | α3j ← α3min if α3j < α3min
      | T2 ← M32(α3j) · TZ
      | T1 ← M21(α2min) · T2
      | T ← M10(α1max) · T1
      | Xj ← T0
      | Yj ← T1
      | T56 ← (Xj, Yj)

```

Grafik dela (0-1-2-3-4-5-6) radne zone bagera

13. Program proračuna na delu (6-7) i crtanja grafika na delu (0-1-2-3-4-5-6-7) radne zone bagera: strela pod uglom α_{1max} ; obrtanje držača kašike od α_{2max} do α_{2min} ; kašika pod uglom α_{3min}

```

T67 := T2 ← M32(α3min) · TZ
      for j ∈ 0..N
      | α2j ← α2min + j · Δα2
      | T1 ← M21(α2j) · T2
      | T ← M10(α1max) · T1
      | Xj ← T0
      | Yj ← T1
      | T67 ← (Xj, Yj)

```

Grafik dela (0-1-2-3-4-5-6-7) radne zone bagera

14. Program proračuna na delu (7-0) i crtanja grafika na delu (0-1-2-3-4-5-6--07) radne zone bagera: strela pod uglom α_{2max} ; obrtanje držača kašike od α_{3min} do α_{3max} , kašika pod uglom α_{3min}

```

T70 := for j ∈ 0..N
      | α3j ← α3min + j · Δα3
      | T2 ← M32(α3j) · TZ
      | T1 ← M21(α2max) · T2
      | T ← M10(α1max) · T1
      | Xj ← T0
      | Yj ← T1
      | T70 ←  $\begin{pmatrix} X \\ Y \end{pmatrix}$ 

```

Grafik dela (0-1-2-3-4-5-6-7-0) radne zone bagera

7.ZAKLJUČAK

Predstavljeni algoritam za proračun i crtanje putanje radnog uređaja bagera sa povratnom kašikom korišćenjem Mathcad alata pruža mogućnost značajnog smanjenja vremena i utroška snage kada su takvi proračuni u pitanju a takođe povezuje data istraživanja sa promenom parametara elemenata radnog uređaja bagera.

8. LITERATURA

- [1]. E.M. Kudryavtsev, "Building cars and the equipment" (with examples of calculations, including and on the computer): The Textbook. – M: Publishing house ASV, (Russia), (2012).
- [2]. E.M. Kudryavtsev, V.V.Stepanov, "Execution of final qualifying work on the computer": the Manual for high schools. - M: the Publishing House "BASTET", (Russia), (2013).
- [3]. E.M. Kudryavtsev, "CAD systems of the machine and the equipment". The Textbook for high schools. M: Publishing house ASV, (Russia), (2013).
- [4]. E.M. Kudryavtsev, "The basis of the automated designing": The textbook for high schools. M: Publishing centre "Academy", p. 304, 2011.
- [5]. E.M. Kudryavtsev, "KOMPAS-3D V10. As much as possible full management". In 2 volumes. M: DMK Press. (Russia), (2018).
- [6]. E.M. Kudryavtsev, "Modeling, design and calculation of mechanical systems". M: DMK Press. p. 400, 2008.
- [7]. E.M. Kudryavtsev, "Practical work on KOMPAS-3D V8: Machine-building libraries". M.: DMK Press/ (Russia), (2007).
- [8]. E.M. Kudryavtsev, "Machine-building designing Mechanical Desktop". M.: DMK Press. (Russia), (2006).

Computer Modelling of a Digging Zone of a Single-bucket Excavator

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The paper shows the technique, algorithm and computer programs in system Mathcad for definition of a working digging zone a single-bucket excavator with the working equipment a return shovel. The working zone of digging of a ground a single-bucket excavator includes several sites. Each site of a zone represents with computer program and graphically in system Mathcad. The offered algorithm of calculation and graphic representation of sites of a digging zone a single-bucket excavator with the working equipment the return shovel allows to reduce on order use time and labour input of such calculations, and also to make the corresponding researches connected about change of parameters of elements of the working equipment.

Keywords: Digging zone, Single-bucket excavator, Technique, Computer program

0. INTRODUCTION

One of the important characteristics a single-bucket excavator is the digging zone, which depends on equipment type, sites of the working equipment, the sizes of elements of the working equipment and corners of their turn. We will consider as an example modelling of a digging zone by excavator with working the equipment a back digger (fig. 1). This digging zone consists of following sites (arches): (0 - 1); (1 - 2); (2 - 3); (3 - 4); (4 - 5); (5 - 6); (6 - 7) (7 - 0). Each of arches of a digging zone has the radius, a turn angle and a center of arches.

Construction of a digging zone is difficult process. It can be executed graphically or analytically. On Fig. 1 the example of a digging zone of a single-bucket excavator with the image of elements of the working equipment is resulted.

Fig. 1. An example of a digging zone by excavator with a back digger

1. KINEMATIC ANALYSIS

The digging zone a single-bucket excavator represents certain sequence of the interconnected sites. For each of sites are known values of turning angles all elements of the working equipment (a boom, a bucket arm and a bucket). The digging zone a single-bucket excavator includes several sites:

- *the first site (0 - 1)* - is formed by turn only a bucket from the maximum turning angle (α_{3max}) when the end of a tooth of a bucket moves from a point 0, to a point 1 laying on a line a boom passing through an axis and an axis of turn of a bucket. Thus turning angles of boom (α_{1max}) and the bucket arm (α_{2max}) do not change;

- *the second site (1 - 2)* - is formed by turn only boom from the maximum turning angle (α_{1max}) to the minimum turning angle (α_{1min}) with the maximum start of a bucket. Thus turning angles of bucket arm and bucket do not change;

- *the third site (2 - 3)* - is formed by turn only a bucket from a point 2 to a point 3. The end of a tooth of a bucket moves from a point 2, to a point 3 laying on a line, a bucket arm passing through an axis and an axis of turn of a bucket. The turning angle a bucket will make – φ (fig. 4). Thus turning angles of boom and bucket arm do not change;

- *the fourth site (3 - 4)* - is formed by turn only bucket arm from the maximum turning angle (α_{2max}) to the minimum turning angle (α_{2min}) with the maximum start when the end of a tooth of bucket moves from a point 3, to a point 4. Thus turning angles of boom and bucket do not change;

- *the fifth site (4 - 5)* - is formed by turn only boom with change turning angle of a boom from the minimum (α_{1min}) to maximum possible (α_{1max}). The end of a tooth of a bucket moves from a point 4, to a point 5. Thus turning angles of a bucket arm and a bucket do not change;

- *the sixth site (5 - 6)* - is formed by turn only a bucket with change of a turning angle from former position to is minimum possible (α_{3min}). The end of a tooth of a bucket moves from a point 5, to a point 6. Thus turning angles of a boom and a bucket arm do not change;

- the seventh site (6 - 7) - is formed by turn only bucket arm from the maximum turning angle (α_{2max}) to its minimum possible (α_{2min}). The end of a tooth of a bucket moves from a point 6, to a point 7. Thus turning angles of a boom and a bucket do not change;

- the eighth site (7 - 0) - is formed by turn only a bucket from its minimum possible (α_{3min}) to the maximum turning angle (α_{3max}). Thus turning angles, a boom and a bucket arm do not change.

As a rule, for simplification of the description of each element of the machinery and the mechanism it is spent in the local system of coordinates adhered to the projected or investigated element (a boom, a bucket arm and a bucket). However, for reception more product general characteristics the detailed description of the interconnected elements already in the basic system of coordinates is required.

2.MODELLING OF A DIGGING ZONE

Modelling of a digging zone of a ground includes:

- construction of a matrix of transition from local system of coordinates of a bucket to local system of a bucket arm;
- construction of a matrix of transition from local system of coordinates of a bucket arm to local system of a boom;
- construction of a matrix of transition from local system of coordinates of a boom to the basic system of coordinates of excavator;
- definition of values of angles of an inclination of a boom, a bucket arm and a bucket in the set ranges;
- consecutive calculation of coordinates of each of sites of a digging zone with use of the developed algorithm of calculation both corresponding programs and representation of results of calculation in a graphic kind.

3.CONSTRUCTION OF A MATRIX OF TRANSITION FROM ONE CO-ORDINATES TO ANOTHER

The basic system of coordinates $0_0X_0Y_0$ excavator - is the system combined with a basic surface (ground) and an axis of rotation of a rotary platform.

The working equipment of a single-bucket excavator has three degrees of freedom. Each element of working equipment (a boom, a bucket arm and a bucket) is defined by function of three angular coordinates: α_1 - a corner of turn of a boom, α_2 - a corner of turn of a bucket arm and α_3 - a corner of turn of a bucket. We will accept, that positive value of angular coordinates of turn of each subsequent system of coordinates corresponds to turn of axes of coordinates counter-clockwise.

Each element of the working equipment has the local system of coordinates: a boom - $0_1X_1Y_1$; a bucket arm - $0_2X_2Y_2$; a bucket - $0_3X_3Y_3$. The beginning of local system of coordinates choose in the basic or connecting hinge of the working equipment. Coordinates of each point of an element of the working equipment to define in the local system of coordinates much easier.

Let's consider in the beginning transformation of coordinates of a point from local system of coordinates on a boom in the basic system of coordinates of excavator.

On fig. 2 are presented the basic system of coordinates $0_0X_0Y_0$ excavator and local system of coordinates of a boom $0_1X_1Y_1$.

Fig. 2. Connection of two adjacent coordinates

Assume, that coordinates of point $T (X_{1T}, Y_{1T})$ in local system of coordinates $0_1X_1Y_1$ boom are known. It is required to define coordinates of this point in the basic system of coordinates $0_0X_0Y_0$ - system of coordinates of excavator.

The coordinate of point T on axis X_1 in system of coordinates $0_0X_0Y_0$ can be defined, using rectangular triangles $0_1d_4d_5$ and d_1d_5T ,

$$X_{0T} = O_1d_4 - d_3d_4 + a1 = O_1d_4 - d_1d_5 + a1, \quad (1)$$

where: O_1d_4 - a side of a rectangular triangle $0_1d_4d_5$;

d_1d_5 - a side of a rectangular triangle d_1d_5T ;

$a1$ - coordinate of the beginning of coordinates of system $0_1X_1Y_1$ on axis X_0 of system $0_0X_0Y_0$.

Knowing value of a turning angle α_1 of system $0_1X_1Y_1$ concerning axis X_0 of system $0_0X_0Y_0$, it is possible to find value of a side of a triangle O_1d_4 from a triangle $0_1d_4d_5$.

$$O_1d_4 = X_{1T} \cdot \cos(\alpha_1). \quad (2)$$

It is possible to find value of a side of a triangle d_1d_5 from a triangle d_1d_5T

$$d_1d_5 = Y_{1T} \cdot \sin(\alpha_1). \quad (3)$$

Substituting expressions (2) and (3) in initial (1), we will receive expression X_{0T}

$$X_{0T} = X_{1T} \cdot \cos(\alpha_1) - Y_{1T} \cdot \sin(\alpha_1) + a1. \quad (4)$$

The coordinate of point T on axis Y_0 in coordinate system of $0_0X_0Y_0$ can be defined, using sides of a triangle of rectangular triangles $0_1d_4d_5$ and d_1d_5T ,

$$Y_{0T} = d_1d_3 + Td_1 + b1 = d_4d_5 + Td_1 + b1, \quad (5)$$

where: d_4d_5 - a side of a rectangular triangle $0_1d_4d_5$;

Td_1 - a side of a rectangular triangle d_1d_5T ;

$b1$ - coordinate of the beginning of coordinates of system $0_1X_1Y_1$ on axis Y_0 of system $0_0X_0Y_0$.

Knowing value of a turning angle α_1 it is possible to find value of a side of a triangle d_4d_5 from a triangle $0_1d_4d_5$.

$$d_4d_5 = X_{1T} \cdot \sin(\alpha_1). \quad (6)$$

It is similarly possible to find value of side of a triangle Td_1 from a triangle d_1d_5T

$$Td_1 = Y_{1T} \cdot \cos(\alpha_1). \quad (7)$$

Substituting expressions (6) and (7) in initial (5), we will receive expression Y_{0T}

$$Y_{0T} = X_{1T} \cdot \sin(\alpha_1) + Y_{1T} \cdot \cos(\alpha_1) + b1. \quad (8)$$

For modelling of movement of working body excavator - a bucket in space we will take advantage of a mathematical apparatus based on representation of entrance and target data in the form of vectors of columns and matrixes of transitions by dimension 4x4. Then, above received expressions of transformation of coordinates of moving, it is possible to present in the form of such matrix expression

$$T = \begin{vmatrix} x_{0T} \\ y_{0T} \\ z_{0T} \\ 1 \end{vmatrix} = \begin{vmatrix} \cos(\alpha_1) & -\sin(\alpha_1) & 0 & a1 \\ \sin(\alpha_1) & +\cos(\alpha_1) & 0 & b1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} x_{1T} \\ y_{1T} \\ z_{1T} \\ 1 \end{vmatrix} = \begin{vmatrix} x_{1T} \cdot \cos(\alpha_1) - y_{1T} \cdot \sin(\alpha_1) + a1 \\ x_{1T} \cdot \sin(\alpha_1) + y_{1T} \cdot \cos(\alpha_1) + b1 \\ z_{1T} \\ 1 \end{vmatrix} \quad (9)$$

4.DETERMINATION OF A TURNING ANGLE OF A BUCKET

Further we will define a turning angle of a bucket on the first site of a digging zone - (0-1). On fig. 3 the scheme of position of elements of the working equipment of excavator for definition a turning angle of a bucket on the first a site of a digging zone (0-1) is presented. A bucket turn on the first site is made on a turning angle $(\alpha_{3max} - \varphi)$ at boom position under a turning angle α_{1max} and bucket arm under a turning angle α_{2max} to a line which are passing through an axis of turn of a boom - O_1 and an axis of turn of a bucket - O_3 , providing the maximum start of a bucket.

Fig. 3. The scheme of position of elements of the working equipment of excavator for definition of a turning angle of a bucket on the first site of a digging zone (0-1)

Using position of the working equipment with as much as possible lifted: a boom, a bucket arm and a bucket fig. 3, we will define:

- coordinates of the centre of turn of bucket $O_3 (X_3, Y_3)$ in local system a boom $O_1 X_1 Y_1$:

$$X_3 = 0_1 B + B X_3 = L_1 \cdot \cos(\alpha_{1max}) + L_2 \cdot \cos(\alpha_{1max} + \alpha_{2max}); \quad (9)$$

$$Y_3 = 0_3 A + A Y_3 = L_2 \cdot \sin(\alpha_{1max}) + L_2 \cdot \sin(\alpha_{1max} + \alpha_{2max}); \quad (10)$$

- coordinates of the centre of turn of bucket $O_3 (X_3, Y_3)$ in the basic system $O_0 X_0 Y_0$:

$$X_{13} = X_3 + a1; \quad (11)$$

$$Y_{13} = Y_3 + b1; \quad (12)$$

- Distance from an axis of a boom to an axis of bucket L_{pc} , m

$$L_{12} = \sqrt{X_3^2 + Y_3^2}, \quad (13)$$

- The corner of turn of a bucket β_{01} on a site (0 - 1) will define from a triangle $O_1 O_2 O_3$ fig. 3, using the theorem косинуса.

$$L_1^2 = L_2^2 + L_{12}^2 - 2 \cdot L_2 \cdot L_{12} \cdot \cos(\varphi); \quad (14)$$

$$\varphi = a \cos\left(\frac{L_2^2 + L_{12}^2 - L_1^2}{2 \cdot L_2 \cdot L_{12}}\right); \quad (15)$$

$$\beta_{01} = \alpha_{3max} - \varphi. \quad (16)$$

Further we will define a turn corner of a bucket on the first site of a digging zone of excavator - (2-3).

On fig. 4 the scheme of position of elements of the working equipment of excavator for construction of a site of a digging zone (2-3) by turning a bucket from a corner 0 to $(-\varphi)$ is presented at boom position under a corner α_{1min} and bucket arm under a corner α_{2max} .

On fig. 4 the scheme of position of elements of the working equipment for definition of a turning angle of a bucket on the third site of a digging zone (2-3) is presented. A bucket turns on the third site is made on a corner $(-\varphi)$ at boom position under a corner α_{1min} and bucket under a corner α_{2max} to a line which are passing through an axis of turn of a bucket arm - O_2 and an axis of turn of a bucket - O_3 , providing the maximum start of a bucket on a following site (3-4) at bucket arm turn.

Fig. 4. The scheme of position of elements of the working equipment of excavator for definition of a corner of turn of a bucket on the third site of a digging zone of excavator (2-3)

5. COMPUTER MODELLING OF A DIGGING ZONE

The algorithm of computer modelling of a digging zone by excavator with the working equipment a return shovel in system Mathcad is presented below.

Input data:

- max and min turning angles of boom in X_0Y_0 plane, ($^\circ$): $\alpha_{1max}=50^\circ$; $\alpha_{1min}=-60^\circ$
- distance between the axis of rotating platform and the axis of boom swing, (m): $a_1=0.2$
- distance between the natural surface of the ground and the axis of boom swing, (m): $b_1=2.0$
- max and min turning angles of bucket arm in X_1Y_1 plane, ($^\circ$): $\alpha_{2max}=-20^\circ$; $\alpha_{2min}=-180^\circ$
- kinematic length of a boom, (m): $L_1=6.5$
- max and min turning angles of bucket arm in X_2Y_2 plane, ($^\circ$): $\alpha_{3max}=30^\circ$; $\alpha_{3min}=-120^\circ$
- kinematic length of a bucket arm, (m): $L_2=3.2$
- kinematic length of a bucket, (m): $L_3=1.64$
- vector of coordinates of a bucket tooth in local coordinates $O_3X_3Y_3$ of a bucket, (m)

$$TZ := (L_3 \ 0 \ 0 \ 1)^T$$

Calculation procedure

- Steps of change of angles of an inclination of boom $\Delta\alpha_1$, bucket arm $\Delta\alpha_2$ and a bucket $\Delta\alpha_3$, radian

$$\Delta\alpha_1 := \frac{\alpha_{1max} - \alpha_{1min}}{N}$$

$$\Delta\alpha_2 := \frac{\alpha_{2max} - \alpha_{2min}}{N}$$

$$\Delta\alpha_3 := \frac{\alpha_{3max} - \alpha_{3min}}{N}$$

- Calculation of the matrix $M32(\alpha_3)$ of transfer from the co-ordinates of a bucket O_3, X_3, Y_3 to the co-ordinates of a bucket arm O_2, X_2, Y_2 and matrix $M21(\alpha_2)$ transfer from the co-ordinates of a bucket arm O_2, X_2, Y_2 to the co-ordinates of a boom O_1, X_1, Y_1

$$M32(\alpha_3) := \begin{pmatrix} \cos(\alpha_3) & -\sin(\alpha_3) & 0 & L_2 \\ \sin(\alpha_3) & \cos(\alpha_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$M21(\alpha_2) := \begin{pmatrix} \cos(\alpha_2) & -\sin(\alpha_2) & 0 & L_1 \\ \sin(\alpha_2) & \cos(\alpha_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Calculation of the matrix $M10(\alpha_1)$ of transfer from the co-ordinates of a boom O_1, X_1, Y_1 to the main co-ordinates of an excavator O_0, X_0, Y_0

$$M10(\alpha_1) := \begin{pmatrix} \cos(\alpha_1) & -\sin(\alpha_1) & 0 & a_1 \\ \sin(\alpha_1) & \cos(\alpha_1) & 0 & b_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Coordinates of the centre of turn of bucket O_3 on a site (0-1)

$$X31 := L_1 \cdot \cos(\alpha_{1max}) + L_2 \cdot \cos(\alpha_{1max} + \alpha_{2max}) + a_1 = 7.149$$

$$Y31 := L_1 \cdot \sin(\alpha_{1max}) + L_2 \cdot \sin(\alpha_{1max} + \alpha_{2max}) + b_1 = 8.579$$

- Distance from an axis of a boom to an axis bucket arm L_{12} , m

$$L_{12} := \sqrt{(X31 - a_1)^2 + (Y31 - b_1)^2} = 9.57$$

- Value of an angle of turn of a bucket on site (0-1), rad., using the cosine theorem

$$\varphi := \arccos\left(\frac{L_2^2 + L_{12}^2 - L_1^2}{2 \cdot L_2 \cdot L_{12}}\right) = 0.234$$

$$\beta_{01} := \alpha_{3max} - \varphi = 0.289$$

- The program of calculation and the graph of a site (0-1) a working zone of an excavator: turn of a bucket from an angle α_{3max} to an angle β_{01} ; a bucket arm under an angle α_{2max} ; a boom under an angle α_{1max} , radian

```

T01 := for j ∈ 0..N
    α3j ← α3max - j · Δα3
    α3j ← α3j if α3j > β01
    α3j ← β01 if α3j < β01
    T2 ← M32(α3j) · TZ
    T1 ← M21(α2max) · T2
    T ← M10(α1max) · T1
    Xj ← T0
    Yj ← T1
    T01 ← (Xj
            Yj)

```

The graph of a site (0-1) working zones of an excavator

8. The program of calculation and the graph of a site (0-1-2) a working zone of an excavator: turn of a boom from angle $\alpha_{1\max}$ to $\alpha_{1\min}$; bucket arm under angle $\alpha_{2\max}$; a bucket under angle β_{01} , radian

```

T12 := | T2 ← M32(β01)·TZ
      | T1 ← M21(α2max)·T2
      | for j ∈ 0..N
      |   α1j ← α1max - j·Δα1
      |   T ← M10(α1j)·T1
      |   Xj ← T0
      |   Yj ← T1
      | T12 ← (Xj, Yj)

```

The graph of a site (0-1-2) working zones of an excavator

9. The program of calculation of a site (2-3) and the graph of a site (0-1-2-3) working zones of an excavator: turn of a bucket from an angle 0 to β_{23} ; a bucket arm under an angle $\alpha_{2\max}$; a boom under an angle $\alpha_{1\min}$, radian

```

β23 := -φ = -0.234
T23 := | for j ∈ 0..N
      |   α3j ← β01 - j·Δα3
      |   α3j ← α3j if α3j > β23
      |   α3j ← β23 if α3j < β23
      |   T2 ← M32(α3j)·TZ
      |   T1 ← M21(α2max)·T2
      |   T ← M10(α1min)·T1
      |   Xj ← T0
      |   Yj ← T1
      | T23 ← (Xj, Yj)

```

The graph of a site (0-1-2-3) working zones of an excavator

10. The program of calculation of a site (3-4) and the graph of a site (0-1-2-3-4) working zones of an excavator: a boom under an angle $\alpha_{1\min}$; turn of a bucket arm from an angle $\alpha_{2\max}$ to $\alpha_{2\min}$; a bucket under an angle 0

```

T34 := | for j ∈ 0..N
      |   α2j ← α2max - j·Δα2
      |   T2 ← M32(β23)·TZ
      |   T1 ← M21(α2j)·T2
      |   T ← M10(α1min)·T1
      |   Xj ← T0
      |   Yj ← T1
      | T34 ← (Xj, Yj)

```

The graph of a site (0-1-2-3-4) working zones of an excavator

11. The program of calculation of a site (4-5) and the graph of a site (0-1-2-3-4-5) working zones of an excavator: turn of a boom from an angle α_{1min} to α_{1max} ; a bucket arm under an angle α_{2min} ; a bucket under an angle 0

```

T45 := for j ∈ 0..N
        α1j ← α1min + j · Δα1
        T2 ← M32(β23) · TZ
        T1 ← M21(α2min) · T2
        T ← M10(α1j) · T1
        Xj ← T0
        Yj ← T1
        T45 ← (Xj
               Yj)

```

The graph of a site (0-1-2-3-4-5) working zones of an excavator

12. The program of calculation of a site (5-6) and the graph of a site (0-1-2-3-4-5-6) working zones of an excavator: a boom under an angle α_{1max} ; a bucket arm under an angle α_{2min} ; turn of a bucket from an angle 0 to α_{3min} .

```

T56 := for j ∈ 0..N
        α3j ← β23 - j · Δα3
        α3j ← α3j if α3j > α3min
        α3j ← α3min if α3j < α3min
        T2 ← M32(α3j) · TZ
        T1 ← M21(α2min) · T2
        T ← M10(α1max) · T1
        Xj ← T0
        Yj ← T1
        T56 ← (Xj
               Yj)

```

The graph of a site (0-1-2-3-4-5-6) working zones of an excavator

13. The program of calculation of a site (6-7) and the graph of a site (0-1-2-3-4-5-6-7) working zones of an excavator: a boom under an angle α_{1max} ; turn of a bucket arm from an angle α_{2max} to α_{2min} ; a bucket under an angle α_{3min}

```

T67 := T2 ← M32(α3min) · TZ
        for j ∈ 0..N
            α2j ← α2min + j · Δα2
            T1 ← M21(α2j) · T2
            T ← M10(α1max) · T1
            Xj ← T0
            Yj ← T1
            T67 ← (Xj
                   Yj)

```

The graph of a site (0-1-2-3-4-5-6-7) working zones of an excavator

14. The program of calculation of a site (7-0) and the graph of a site (0-1-2-3-4-5-6-7-0) working zones of an excavator a boom under an angle $\alpha_{2\max}$; a bucket arm under an angle $\alpha_{2\max}$; turn of a bucket from an angle $\alpha_{3\min}$ to $\alpha_{3\max}$

```

T70 := for j ∈ 0..N
      α3j ← α3min + j · Δα3
      T2 ← M32(α3j) · T2
      T1 ← M21(α2max) · T2
      T ← M10(α1max) · T1
      Xj ← T0
      Yj ← T1
      T70 ←  $\begin{pmatrix} X \\ Y \end{pmatrix}$ 

```

The graph of a site (0-1-2-3-4-5-6-7-0) working zones of an excavator

7. CONCLUSION

The offered algorithm of calculation and graphic representation of sites of a digging zone excavator with the working equipment the return shovel allows to reduce on order with system Mathcad use time and labour input of such calculations, and also to make the corresponding researches connected about change of parameters of elements of the working equipment.

REFERENCES

- [1]. E.M. Kudryavtsev, "Building cars and the equipment" (with examples of calculations, including and on the computer): The Textbook. – M: Publishing house ASV, (Russia), (2012).
- [2]. E.M. Kudryavtsev, V.V.Stepanov, "Execution of final qualifying work on the computer": the Manual for high schools. - M: The Publishing House "BASTET", (Russia), (2013).
- [3]. E.M. Kudryavtsev, "CAD systems of the machine and the equipment". The Textbook for high schools. M: Publishing house ASV, (Russia), (2013).
- [4]. E.M. Kudryavtsev, "The basis of the automated designing": The textbook for high schools. M: Publishing centre "Academy", p. 304, 2011.
- [5]. E.M. Kudryavtsev, "KOMPAS-3D V10. As much as possible full management". In 2 volumes. M: DMK Press. (Russia), (2018).
- [6]. E.M. Kudryavtsev, "Modeling, design and calculation of mechanical systems". M: DMK Press. p. 400, 2008.
- [7]. E.M. Kudryavtsev, "Practical work on KOMPAS-3D V8: Machine-building libraries". M.: DMK Press/ (Russia), (2007).
- [8]. E.M. Kudryavtsev, "Machine-building designing Mechanical Desktop". M.: DMK Press. (Russia), (2006).