THE DISPLACEMENT OF THE EXCAVATOR BUCKET ON THE OPTIMUM TRAJECTORY THROUGH THE CONTROL OF THE HYDRAULIC CYLINDERS LENGTHS *

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Abstract. The article refers to the hydraulic excavators with backhoe attachment equipped with length sensors at the hydraulic cylinders. The relations for the calculus of the lengths of the hydraulic cylinders of the excavator corresponding to a given position of the bucket cutting edge are established. These relations are necessary for the indication of the bucket position in the excavator cabin as well as for the automatic command of the working equipment of the excavator for obtaining an optimum trajectory of the bucket. An application for a concrete case was realized.

Key words: hydraulic excavator, bucket position control, hydraulic cylinders, length magnetostrictive sensors.

1. INTRODUCTION

The indication of the bucket position in the cabin is necessary for increasing of the productivity and the precision of execution at the digging works with excavators. The realization of this objective supposes the mounting of some position sensors on the working equipment of the excavator. One of the possibilities is utilization of the length magnetostrictive sensors at hydraulic cylinders, which drive boom, stick and bucket.

The existence of these sensors on the working equipment creates the possibility of achievement of some automatic systems for obtaining an optimum trajectory of the bucket cutting edge.

For the utilization of the length sensors at excavator hydraulic cylinders, the following problems are necessary to be solved:

- the determination of the position angles of the boom, stick and bucket corresponding to a given position of the bucket;
- the determination of the boom cylinder length depending on the boom position angle;

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- the determination of the stick cylinder length depending on the stick and boom position angle;
- the determination of the bucket cylinder length depending on the bucket, stick and boom position angle.
- the creation of the electronic system which indicates in the cabin the bucket position in function of the hydraulic cylinders lengths and also of the automatic command system of the hydraulic cylinders considering the imposed digging trajectory.

2. THE FUNCTIONING PRINCIPLE OF THE LENGTH SENSOR FOR THE HYDRAULIC CYLINDERS

The sensors for the measurement of the hydraulic cylinder length rely on the principle of magnetostriction, which is based on the property of some magnetic materials for modifying the dimension or the shape when are introduced through a magnetic field. The magnetostrictive position sensors have a higher reliability and assure a very good measuring precision.

The Wiedemann effect appears at the magnetostrictive materials. This effect consists on the producing of some torsion of a wire from a magnetostrictive material covered by an electric current, in the place in which a permanent magnet is positioned. If through a wire from a magnetostrictive material, a pulsating current of higher frequency circulates, the Wiedemann effect produces a torsion/ ultrasonic wave, which is propagated through the wire length with the sound speed.

The functioning scheme of a length magnetostrictive sensor is indicated in Figure 1 [1].

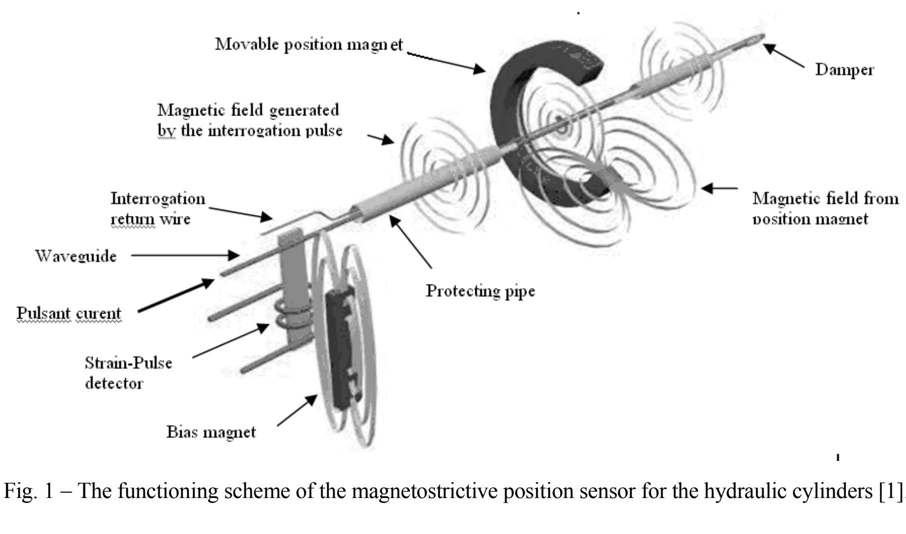

Fig. 1 – The functioning scheme of the magnetostrictive position sensor for the hydraulic cylinders [1].

An interaction of a magnetic field generated by the pulsating current from the wire with the magnetic field of a mobile permanent magnet takes place. The mobile magnet is mounted on the element of which position has to be determined and the position determination is realized through the measuring of the propagation time of the torsion wave from the place of the wave generation (the place where is the magnet) until the detection device of the wave. The detection device is based on the Viralli effect, which consists in the way that applying against a magnetostrictive material a force the modification of the magnetic properties of it is produced. A device of measuring the time (timer) is started at the same moment with the introducing of the pulsating current and is closed when the wave arrives at the detection device. The electronic device assures the displaying of the distance in function of the measured propagation time.

In Figure 2, the mounting of the magnetostrictive position sensor on the hydraulic cylinder is indicated [1].

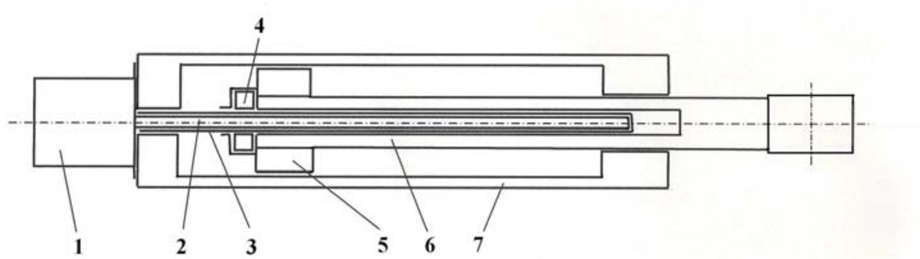

Fig. 2 – The mounting scheme of the magnetostrictive position sensor on the hydraulic cylinder [1].

1– body of the sensor; 2– waveguide from magnetostrictive material; 3– protection pipe; 4– movable position magnet; 5– piston; 6– stem of the hydraulic cylinder; 7– body of the hydraulic cylinder.

The mobile magnet 4, in the shape of a ring, is mounted on the hydraulic cylinder piston 5, and the wire from magnetostrictive material 2 together with the carcass 1 in which is located the detection system of the wave and the system of introducing of a pulse current are fixed on the hydraulic cylinder body through a flange. The wire is passing through the interior of the hydraulic cylinder stem 6. This construction assures easier mounting and disassembling of the sensor, without the reduction of the pressure in the hydraulic cylinder.

In function of the lengths of the cylinders indicated by the sensors, the computer installed on the excavator can determine in any moment the cutting edge position of the bucket and the desired trajectory of the bucket is possible to be obtained.

3. THE CALCULATION OF THE POSITION ANGLES OF THE BOOM, STICK AND THE BUCKET CORRESPONDING TO A GIVEN POSITION OF THE BUCKET [9]

The following known parameters are considered (Fig. 3): the distances $O_1O_2 = l_1$, $O_2O_3 = l_2$, $O_3O_4 = l_3$, and also position angle of the bucket α_3, where O_1 is the joint of the boom at the basis machine, O_2 the joint between the boom and the stick, O_3 the joint between the stick and the bucket, O_4 the cutting edge of the bucket.

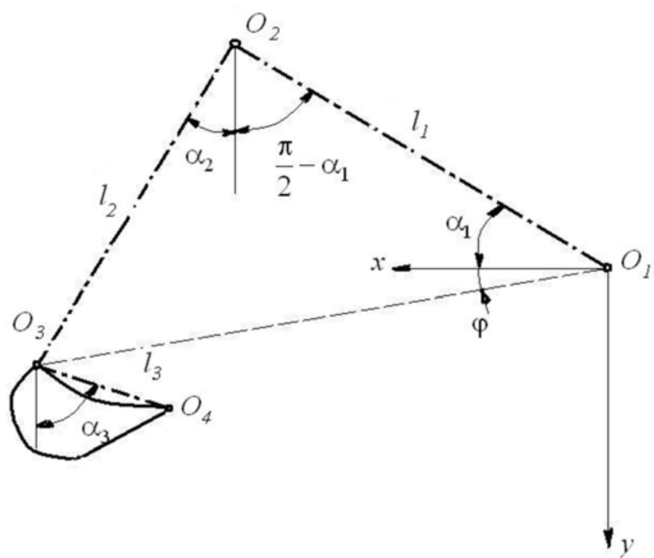

Fig. 3 – The scheme for the calculus of the position angles for the stick and boom.

For the calculus of the length of the manoeuvre hydraulic cylinders of the working equipment, knowing the coordinates x_{O4}, y_{O4} of the bucket cutting edge O_4 and the bucket position angle α_3, the following stages are covered:

- The coordinate x_{O3}, y_{O3} of the joint O_3 between stick and bucket are determined by the relations:

$$x_{O_3} = x_{O_4} + l_3 \sin\alpha_3 \tag{1}$$

$$y_{O_3} = y_{O_4} - l_3 \cos\alpha_3 \tag{2}$$

- The distance O_1O_3 and the angle φ are determined by the relations:

$$\mathrm{O_1O_3} = \sqrt{x_{\mathrm{O_3}}^2 + y_{\mathrm{O_3}}^2} \tag{3}$$

$$\varphi = \mathrm{arctg}\frac{y_{\mathrm{O_3}}}{x_{\mathrm{O_3}}} \tag{4}$$

- The angle $\sphericalangle \mathrm{O_1O_2O_3}$ is determined, applying the cosine theorem in the triangle $\Delta \mathrm{O_1O_2O_3}$:

$$\sphericalangle \mathrm{O_1O_2O_3} = \arccos\frac{l_1^2 + l_2^2 - \mathrm{O_1O_3}^2}{2 \cdot l_1 \cdot l_2} \tag{5}$$

- The sine theorem is applied in the triangle $\Delta \mathrm{O_1O_2O_3}$ and the angle $\sphericalangle \mathrm{O_2O_1O_3}$ is determined:

$$\frac{\mathrm{O_1O_3}}{\sin(\sphericalangle \mathrm{O_1O_2O_3})} = \frac{l_2}{\sin(\sphericalangle \mathrm{O_2O_1O_3})} \tag{6}$$

$$\sphericalangle \mathrm{O_2O_1O_3} = \arcsin\left(\frac{l_2 \cdot \sin \sphericalangle \mathrm{O_1O_2O_3}}{\mathrm{O_1O_3}}\right) \tag{7}$$

- The tilt angle α_1 of the boom axis towards the horizontal axis O*x* is determined:

$$\alpha_1 = \sphericalangle \mathrm{O_2O_1O_3} - \varphi \tag{8}$$

- The tilt angle α_2 of the stick axis towards the vertical axis is determined:

$$\alpha_2 = \sphericalangle \mathrm{O_1O_2O_3} - \left(\frac{\pi}{2} - \alpha_1\right) \tag{9}$$

- Knowing the angles α_1, α_2, α_3, the lengths of the boom, stick and the bucket manoeuvre cylinders using the relations established below are determined.

4. THE CALCULATION OF THE LENGTH OF THE BOOM CYLINDER [9]

Using the scheme from Fig. 4, the length of the boom cylinder AB is determined in function of the tilt angle α_1 of the boom axis $\mathrm{O_1O_2}$ towards the horizontal axis Ox. The construction of the boom and the boom manoeuvre cylinder joints position are supposed known, so that the lengths $\mathrm{O_1B}$, $\mathrm{O_2B}$, $\mathrm{O_1O_2}$, $\mathrm{O_1D}$, AD are known.

The following stages are covered:

- The angle β is determined by the relation:

$$\beta = \text{arctg}\frac{O_1D}{AD} \tag{10}$$

-Applying the cosine theorem in the triangle ΔO_1O_2B the angle γ is obtained:

$$\gamma = \arccos\frac{O_1O_2{}^2 + O_1B^2 - O_2B^2}{2 \cdot O_1O_2 \cdot O_1B} \tag{11}$$

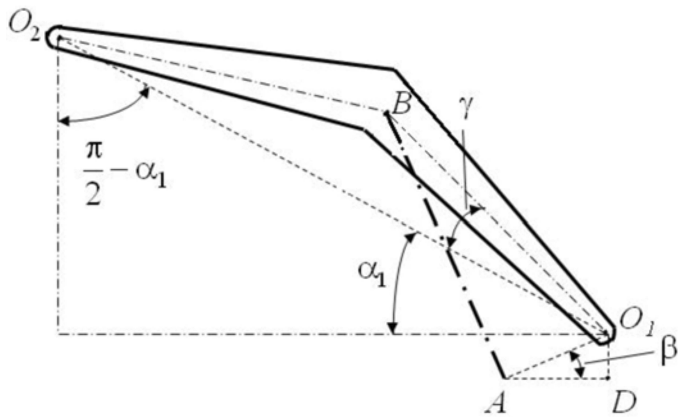

Fig. 4 – Scheme for the boom manoeuvre cylinder length calculus.

- O_1A is determined from the rectangle triangle ΔO_1AD:

$$O_1A = \sqrt{AD^2 + O_1D^2} \tag{12}$$

- The angle $\sphericalangle AO_1B$ is determined:

$$\sphericalangle AO_1B = \alpha_1 + \beta + \gamma \tag{13}$$

- The length of the boom cylinder AB is determined applying the cosine theorem in the triangle ΔAO_1B:

$$AB = l_{c_1} = \sqrt{O_1B^2 + O_1A^2 - 2 \cdot O_1B \cdot O_1A \cdot \cos\sphericalangle AO_1B} \tag{14}$$

5. THE CALCULATION OF THE STICK CYLINDER LENGTH [9]

Using the scheme from Figure 5, the length of the stick manoeuvre cylinder is determined in function of the tilt angle α_2 of the stick axis O_2O_3 towards the vertical, and also in function of tilt angle α_1 of the boom towards the horizontal. The construction of the stick and the position of the stick manoeuvre cylinder joints are supposed known, so that the lengths O_2F, O_2O_3, O_3F, O_2E, O_1E, O_1O_2 are known.

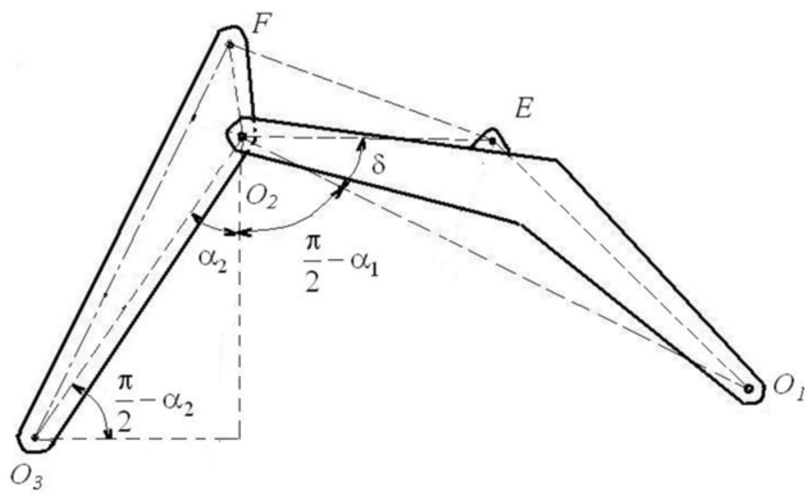

Fig. 5 – Scheme for the stick cylinder length calculus.

The following stages are covered:

- The angle $\sphericalangle FO_2O_3$ is determined applying the cosine theorem in the triangle:

$$\sphericalangle FO_2O_3 = \arccos\frac{O_2F^2 + O_2O_3{}^2 - O_3F^2}{2 \cdot O_2F \cdot O_2O_3} \quad (15)$$

- The angle δ is determined applying the cosine theorem in the triangle ΔO_1O_2E:

$$\delta = \arccos\frac{O_2E^2 + O_1O_2{}^2 - O_1E^2}{2 \cdot O_2E \cdot O_1O_2} \quad (16)$$

- The angle $\sphericalangle EO_2F$ is determined through the subtraction:

$$\sphericalangle EO_2F = 2 \cdot \pi - (\sphericalangle FO_2O_3) - \alpha_2 - \left(\frac{\pi}{2} - \alpha_1\right) - \delta \quad (17)$$

- The stick cylinder length EF is determined, applying the cosine theorem in the triangle ΔEO_2F:

$$EF = l_{c_2} = \sqrt{O_2F^2 + O_2E^2 - 2 \cdot O_2F \cdot O_2E \cdot \cos \sphericalangle EO_2F} \qquad (18)$$

6. THE CALCULATION OF THE BUCKET MANOEUVRE CYLINDER LENGTH [9]

The position angles α_1, α_2, α_3 of the working equipment are considered known (§3).

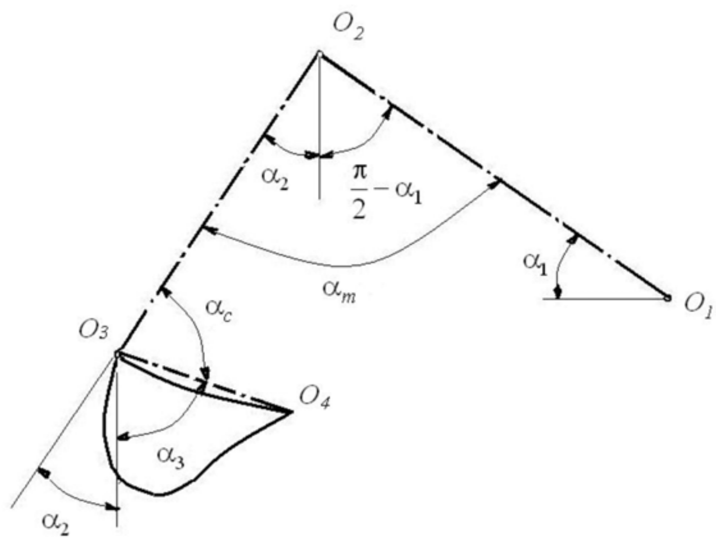

Fig. 6 – The position angles of the working equipment.

From Figure 6 the angles α_m, α_c result:

$$\alpha_m = \alpha_2 + \frac{\pi}{2} - \alpha_1 \qquad (19)$$

$$\alpha_c = \pi - \alpha_2 - \alpha_3 \qquad (20)$$

in which α_m is the angle between the boom axis O_1O_2 and the stick axis O_2O_3, α_c is the angle between the stick axis O_2O_3 and the axis O_3O_4, which unifies the joint O_3 between the stick and bucket with the bucket cutting edge O_4.

The construction of the stick and the bucket are considered known, and also the construction of the bucket manoeuvre mechanism, so that the distances O_2J, O_3J, O_2O_3, O_2L, O_3L, LM, MN, O_3N are known. The bucket manoeuvre cylinder length LM is determined covering the following stages:

-The angle $\sphericalangle NO_3O_4$ is determined applying the cosine theorem in the triangle ΔNO_3O_4:

$$\sphericalangle NO_3O_4 = \arccos\frac{O_3N^2 + O_3O_4{}^2 - NO_4{}^2}{2\cdot O_3N\cdot O_3O_4} \tag{21}$$

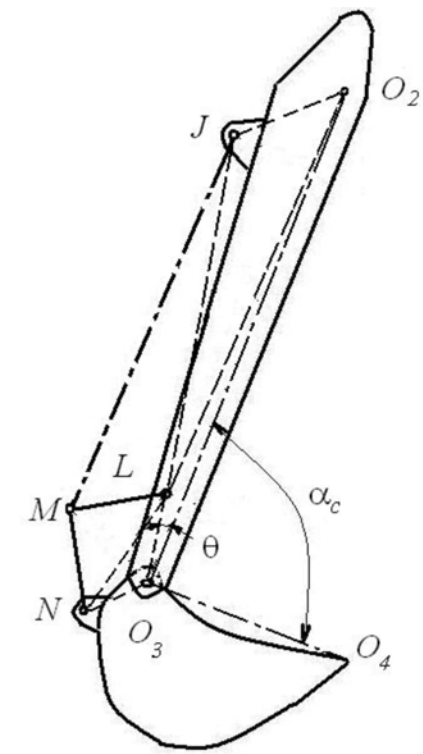

Fig. 7 – Scheme for the bucket manoeuvre cylinder length determination.

- The angle θ is determined applying the cosine theorem in the triangle ΔO_2O_3L:

$$\theta = \arccos\frac{O_3L^2 + O_2O_3{}^2 - O_2L^2}{2\cdot O_3L\cdot O_2O_3} \tag{22}$$

- The angle $\sphericalangle LO_3N$ is determined through difference:

$$\sphericalangle LO_3N = 2\pi - \alpha_c - \theta - (\sphericalangle NO_3O_4) \tag{23}$$

- The angle $\sphericalangle O_2LO_3$ is determined applying the cosine theorem in the triangle ΔO_2LO_3:

$$\sphericalangle O_2LO_3 = \arccos\frac{O_2L^2 + O_3L^2 - O_2O_3{}^2}{2 \cdot O_2L \cdot O_3L} \tag{24}$$

- The angle $\sphericalangle O_2LJ$ is determined applying the cosine theorem in the triangle ΔO_2LJ:

$$\sphericalangle O_2LJ = \arccos\frac{O_2L^2 + JL^2 - O_2J^2}{2 \cdot O_2L \cdot JL} \tag{25}$$

- LN is determined applying the cosine theorem in the triangle ΔO_3LN:

$$LN = \sqrt{O_3L^2 + O_3N^2 - 2 \cdot O_3L \cdot O_3N \cdot \cos\sphericalangle LO_3N} \tag{26}$$

- The angle $\sphericalangle O_3LN$ is determined applying the sine theorem in the triangle ΔO_3LN:

$$\sphericalangle O_3LN = \arcsin\frac{O_3N \cdot \sin\sphericalangle LO_3N}{NL} \tag{27}$$

- The angle $\sphericalangle MLN$ is determined applying the cosine theorem in the triangle ΔMLN:

$$\sphericalangle MLN = \arccos\frac{LM^2 + LN^2 - MN^2}{2 \cdot LM \cdot LN} \tag{28}$$

- The angle $\sphericalangle JLM$ is determined through difference:

$$\sphericalangle JLM = 2\pi - (\sphericalangle O_2LO_3) - (\sphericalangle O_2LJ) - (\sphericalangle O_3LN) - (\sphericalangle MLN) \tag{29}$$

- Applying the cosine theorem in the triangle ΔJLM, the bucket manoeuvre cylinder length JM is determined, corresponding to the position angles of the working equipment α_1, α_2, α_3:

$$JM = l_{c_3} = \sqrt{JL^2 + LM^2 - 2 \cdot JL \cdot LM \cdot \cos\sphericalangle JLM} \tag{30}$$

7. APPLICATION

Using the relations established above, the condition that the bucket cutting edge describe a horizontal surface (Fig. 8) can be established, a problem which presents importance at the dug surface finishing by the excavator.

The application was realized in a concrete case, for which the parameters from the relations (1)-(30) and which are defined in the Figures 3-8 have the values from the Table 1. Bucket tilt angle towards the ground ε_1 is constant, so that the position angle of the bucket α_3 is constant.

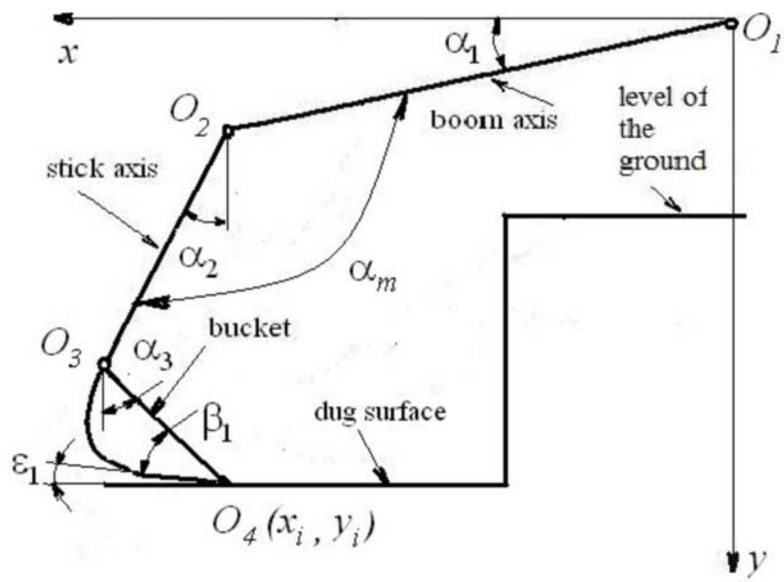

Fig. 8 – The finishing of horizontal surface by the excavator.

For different points of the dug trajectory, the position angles of the boom and of the stick and then the hydraulic cylinders lengths of the stick, boom and bucket were calculated using a MATLAB program, realized with the relations (1)-(30).

Table 1

Values and measurement units	Figure in which are defined
$O_1O_2 = 6.466$ m; $O_2O_3 = 3.133$ m; $O_3O_4 = 1.866$ m	Fig.3
$O_1B = 2.400$ m; $O_1A = 0.933$ m	Fig.4
$O_2E = 3.626$ m; $O_2F = 1.200$ m	Fig.5
$JL = 2.800$ m; $ML = 0.800$ m	Fig.7
$NM = 0.666$ m; $O_3L = 0.440$ m	Fig.7
$\beta = 0.68$ rad; $\gamma = 0.383$ rad	Fig.4
$\sphericalangle FHO_3 = 2.738$ rad; $\delta = 0.3623$ rad	Fig.5
β_1=0.872 rad; $\varepsilon_1 = 0.174$ rad; $\alpha_3 = 0.5248$ rad	Fig.8
$h = 2.1$ m; $x_i = 7.0$ m; $y_i = 5.1$ m	Fig.8

The necessary correlation between the hydraulic cylinders lengths results for obtaining the desired horizontal trajectory of the bucket cutting edge.

In the same way the correlation between the hydraulic cylinders lengths of the excavator at the digging of a tilted surface towards the horizontal with a certain angle or at the equipment manoeuvre in other stages of the working cycle can be established.

This correlation between the hydraulic cylinders lengths necessary to obtain a horizontal surface is indicated in Figure 9, in which the curve 1 represents the variation of the bucket cylinder length in function of the stick cylinder length, and the curve 2 represents the variation of the boom cylinder length in function of the stick cylinder length.

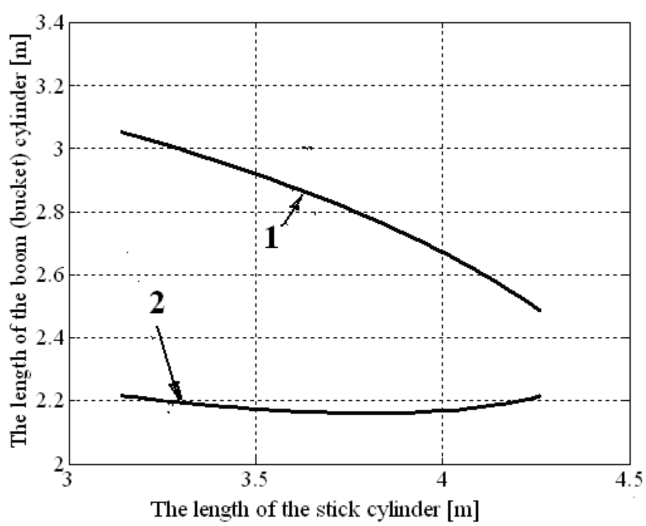

Fig. 9 – The correlation between the hydraulic cylinders lengths for obtaining a horizontal trajectory of the bucket cutting edge.

8. CONCLUSIONS

The automatic command systems, which assure the obtaining of the desired trajectory of the bucket, can be designed with the aid of the established relations from above, which allow the calculus of the hydraulic cylinders lengths for the manoeuvre of the boom, the stick and the bucket for each point of the bucket cutting edge trajectory. The sensors mounted on the hydraulic cylinders transmit all the time data concerning the bucket position, and assure the possibility of the automatic execution of the excavator digging trajectory.

In the future, through the utilization on a wide scale of the improvements from the high technical domains (cybernetics, microelectronics, sensor techniques, mechatronics, laser techniques, communications through satellite – GPS) in the domain of the excavators, the degree of automatization of the working cycle operations will increase gradually, with the tendency of utilization in the hard working conditions of the robot excavators.

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