RESEARCH ON THE KINEMATICS AND DYNAMICS OF FRONT LOADERS MOUNTED ON AGRICULTURAL WHEEL TRACTORS

S. Popescu, I. Candea and C. Csatlos

Abstract: *For the constructive and functional optimisation of the systems consisting of tractor and front loader, the paper analyses the kinematics and dynamics of front loader working equipment. The theoretical research is carried out based on the mathematical models describing the kinematics and dynamics of the loader arm, which is jointed to the tractor body and driven (for lifting and lowering, respectively) by hydraulic cylinders. Based on the developed mathematical models the influence of various constructive and functional parameters of the loader on the working process is studied by computer-aided simulation. The study is exemplifies on a concrete system consisting of the U-650 wheel tractor and the IF-65 front loader, both of Romanian make.*

Keywords: *agricultural tractor; front loader; kinematic model; dynamic model; mathematical model; computer-aided simulation.*

KINEMATICS OF THE LIFTING MECHANISM

Agricultural wheel tractors equipped with front loaders are at present increasingly used for agricultural products and materials loading-unloading and manipulating operations. In order to study the dynamics of front loaders a system of coordinates/frame of reference *xOz* in the longitudinal plane is considered, its origin O being the contact point of the track with the wheels of the rear axle (fig. 1). Considering the coordinates of the lifting arm's and hydraulic cylinder's joints to the tractor body, that is *A* (x_A, z_A) and *B* (x_B, z_B) respectively and the distance *a* between joint *A* of the arm and joint C of the cylinder rod to the arm and the distance *l* between joint *A* and joint *D* of the bucket, the kinematics and dynamics of the loader arm can be analysed in dependence on the rotation angle φ of the arm. In order to ensure the plane – parallel motion of the lifting organ during lifting (such as to maintain the material in the bucket in an adequate position), the bucket is linked to the loader arm by a deformable four-link (parallelogram) mechanism.

The basic aspects related to the kinematics of the front loader reside in the determination, in dependence on the rotation angle φ of the arm, of the trajectory of arm joint *D* and of the distance *BC* (representing the length of the opening of the hydraulic cylinder), wherefrom the stroke of the cylinder piston rod can be established. The coordinates of points *D* and *C* in dependence on the geometric parameters *l, a*, and α of the arm and the coordinates of the hinge point *A* (x_A, z_A) of the arm to the tractor body, as well as distance *BC* are determined with the following relationships:

- for point *C* (the joint of the arm with the tractor body):

$$x_C = x_A + a\cos\varphi\,; \qquad z_C = z_A + a\sin\varphi\,. \tag{1}$$

- for point *D* (the joint of the bucket with the lifting arm):

$$x_D = x_A + l\cos(\varphi - a)\,; \qquad z_D = z_A + l\sin(\varphi - a)\,. \tag{2}$$

- the distance *BC* (the working length of the cylinder):

$$\overline{BC} = \sqrt{(x_A + a\cos\varphi - x_B)^2 + (z_A - a\sin\varphi - z_B)^2}\ . \tag{3}$$

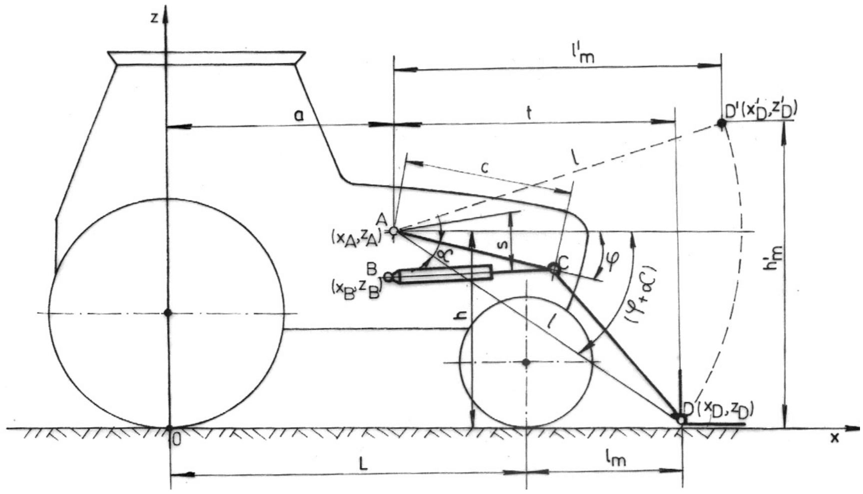

Fig. 1. Computation diagram of the lifting arm kinematics

The trajectory of point D can be determined analytically based on equations (3) and (4) or graphically. Thus the optimum position of point A can be identified, such as to obtain the indicated functional parameters. In figure 32 the trajectories of point *D* were plotted for various positions of point *A* and the same arm length *l*. Curve 3 represents the trajectory of the IF-65 front loader arm mounted on the U-650 wheel tractor, which has the following constructive parameters: *L= 2430 mm; l = 2460 mm; a = 1700 mm; h = 1580 mm*; $\propto = 12^{0}$

The study of the lifting arm kinematics can be achieved also by establishing the dependence between the distance l_m of joint D from the front axle of the tractor and h_m, the lifting height of the bucket from the road surface.
With the notations of figure 1, the magnitudes l_m and h_m are given by the expressions:

$$l_m = a + l\cos(\varphi + \alpha) - L; \tag{4}$$

$$h_m = h - l\sin(\varphi + \alpha). \tag{5}$$

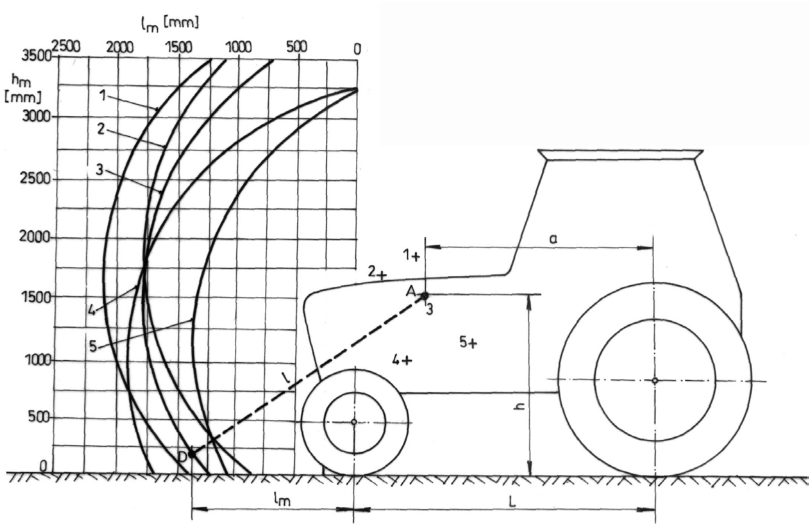

Fig..2 Trajectories of the bucket joint D for various positions of the joining point A of the arm and tractor

From equation (9) the expression for the determination of the rotation angle φ of the arm is obtained:

$$\varphi = \left[\arcsin\left(\frac{h-h_m}{l}\right) - \alpha \right]. \quad (6)$$

By introducing the expression of angle φ given by expression (6) into expression (4) the variation function of distance l_m in relation to the lifting height h_m of the bucket is obtained, that is l_m = f (h_m), given by equation :

$$l_m = l\cos\left[\arcsin\left(\frac{h-h_m}{l}\right) - \alpha \right] - (L-a) \quad . \quad (7)$$

Figure 3 shows the graph of function l_m = f *(* h_m) applied to the front loader IF-65 mounted on the U-650 tractor. The variation curves l_m = f *(* h_m) are also plotted in figure 2, where curve 3 represents the situation for the front loader IF-65.

It can be noticed that distance l_m has a maximum when the loader arm (straight line *AD*) is in a horizontal position.

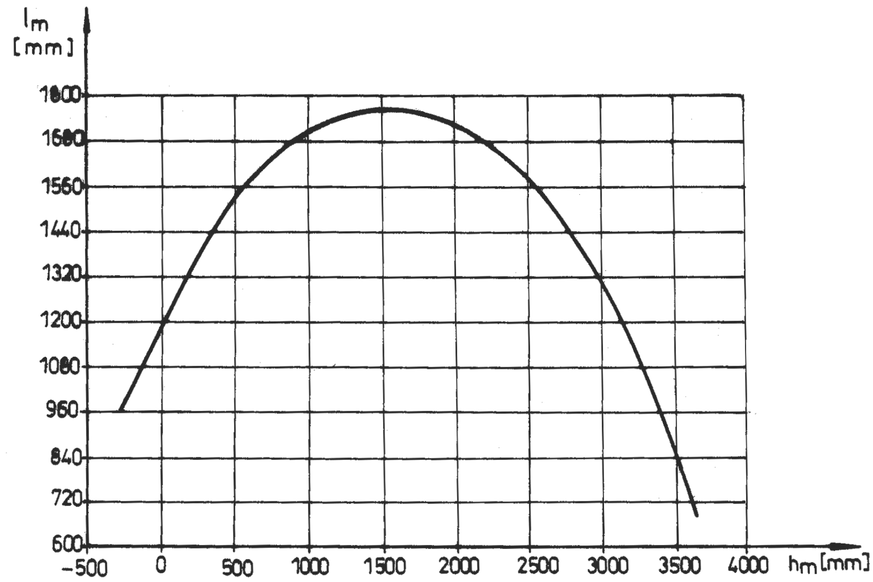

Fig.3. Variation of the longitudinal coordinate l_m versus height h_m of the loader bucket

The analysis of the kinematics of the loader arm can be achieved also in function of the lifting height *h* from the soil surface of joint D ($h = x_D$) depending on the stroke *d* of the arm actuating hydraulic cylinder (*d* = *BC*). For this purpose equations (2) and (6) are used, wherefrom eventually follows the variation function of the arm rotation angle φ depending on the hydraulic cylinder stroke *d*, given by equation:

$$\varphi = 2\, arc\, tg\left(\frac{-c^2q^2 - \sqrt{cq^2 - q_3d^2 + cq^2{}_1}}{q_3d - cq_1} \right), \quad (8)$$

where coefficients q_1, q_2 and q_3 are given by the expressions:

$$q_1 = x_A - x_B; \qquad q_2 = z_B - z_{A;} \qquad q_3 = \frac{q^2{}_1 + q^2{}_2 + c^2 - d^2}{2}. \quad (9)$$

The graph of variation of the arm rotation angle φ depending on the lifting hydraulic cylinder stroke determined with equation (8) is shown in figure 4.

By introducing angle φ given by expression (8) into equations (4) and (5) the expressions follow for the computation of coordinates l_m and h_m of the bucket joint depending on stroke *d* of the hydraulic cylinder, that is $l_m=f(d)$ and $h_m=f(d)$. Figure 5 shows the graph of these functions.

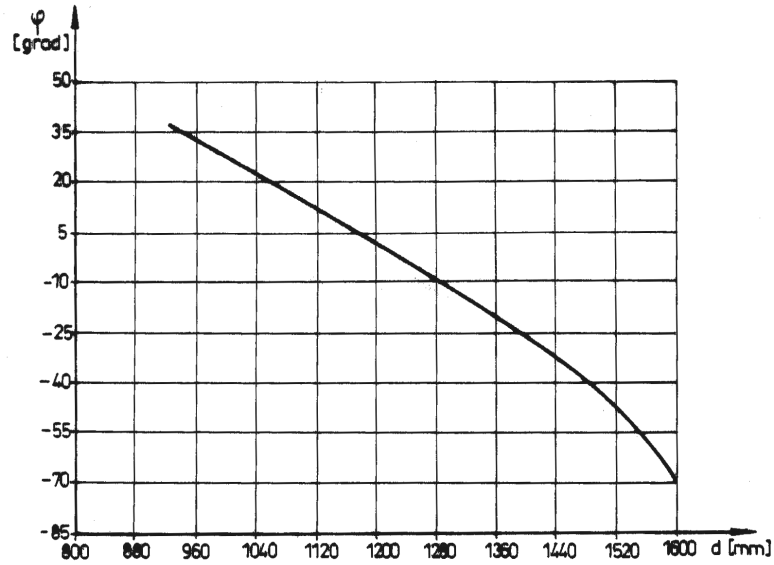

Fig.4. Variation of the arm rotation angle φ versus the lifting hydraulic cylinder stroke

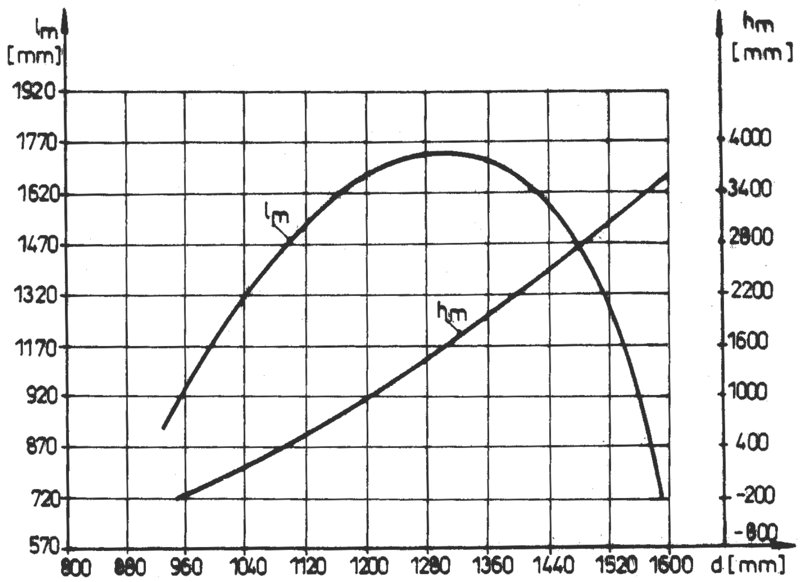

Fig. 5. Variation of the coordinates l_m and h_m of the bucket joint depending on stroke d of the hydraulic cylinder

Functions $h_m = f(d)$ and $l_m = f(d)$ can be used for the indirect experimental determination of the bucket lifting height h_m depending on the stroke d of the hydraulic cylinder of the arm (a parameter measured directly within experimental research).

DYNAMICS OF THE LIFTING MECHANISM

In the lifting process of the working element the loader arm is subjected in point D to the action of the resulting force F_m (including the own weight of the arm) (fig.6). The lifting of the arm is achieved under the action in point *C* of the force F_z from the hydraulic cylinder rod (with joint B). In the joint of the arm to the tractor (point A) reaction R_A is generated.

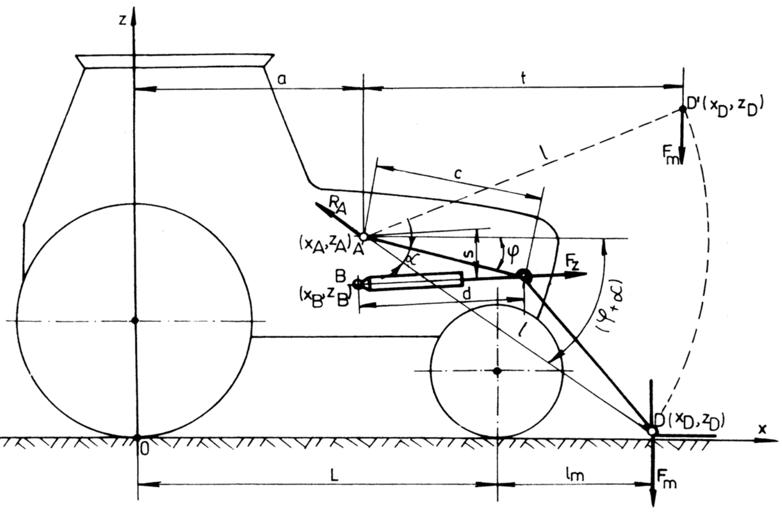

Fig. 6. Computation diagram for the dynamics of the lifting arm

The distance from the joining point A of the cylinder to straight line BC (defined by points *B* (x_B, z_B) and C (x_C, z_C) represents the arm *s* of force F_z from the hydraulic cylinder rod in relation to the joining point of the arm $A(x_A, z_A)$. The arm *t* of force F_m which acts in the joint *D* of the bucket represents the projection on axis *OX* of the arm *l*= *AD*, that is:

$$t = l\,cos(\varphi - a) \qquad (10)$$

From the equilibrium equation of the arm the variation can be determined of the ration of force F_m acting upon the working element (bucket) and force F_z, developed by the hydraulic cylinder, depending on the rotation angle φ from the inferior limit position. Subsequently to mathematical transformations, the final equation for the F_m/F_z ratio depending on the rotation angle φ will have the form:

$$\frac{F_m}{F_z} = \frac{c}{l\cos(\varphi - a)} \cdot \frac{(x_B - x_A)\sin\varphi - (z_B - z_A)\cos\varphi}{\sqrt{(x_A - x_B + a\cos\varphi)^2 + (z_A - z_B + a\sin\varphi)^2}} . \qquad (11)$$

In order to express ratio (k = F_z/F_m) depending on the lifting height of the arm h_m ($h_m = z_D$), the expression of the angle φ given by equation (6) is replaced by the one given by equation (11). By adequate mathematical transformations finally the expression of the ratio $F_z/F_m = f(h_m)$ is obtained, given by equation:

$$\frac{F_z}{F_m} = \frac{1}{s} l \cos\left[\arcsin\frac{(h - h_m)}{L} - \alpha\right], \qquad (12)$$

where the arm *s* represents the distance from point *A* to the straight line *BC* and is given by the expression:

$$s = \frac{(z_B - z_C)a + (x_C - x_B)h + (x_B z_C - x_C z_B)}{\sqrt{(z_B - z_C)^2 \cdot (x_C - x_B)^2}}. \tag{13}$$

The analysis of the variation of function $F_z/F_m = f(h_m)$ was achieved by computer simulation of the system consisting of the U – 650 M wheel tractor and the IF – 65 front loader, using the concrete numerical values, that is $x_A = a = 1700$ mm; $z_A = h = 1580$ mm, $x_B = 1760$ mm; $z_B = 1125$ mm; $l = 2460$ mm; $c = 1180$ mm; $L = 2430$ mm; $\beta = 12^0$. The variation of ratio F_z/F_m depending on the height h_m of the bucket for this system is plotted in figure 7.

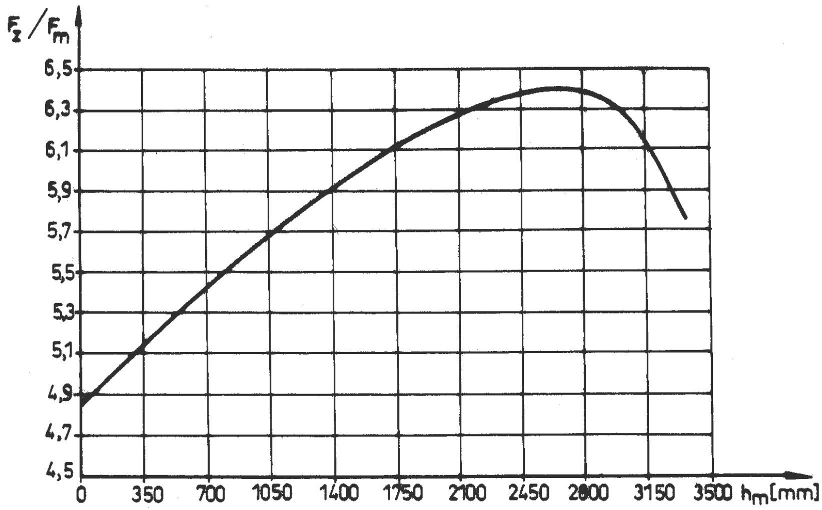

Fig. 7. Variation of the F_z/ F_m ration depending on the height of the loader bucket height h_m

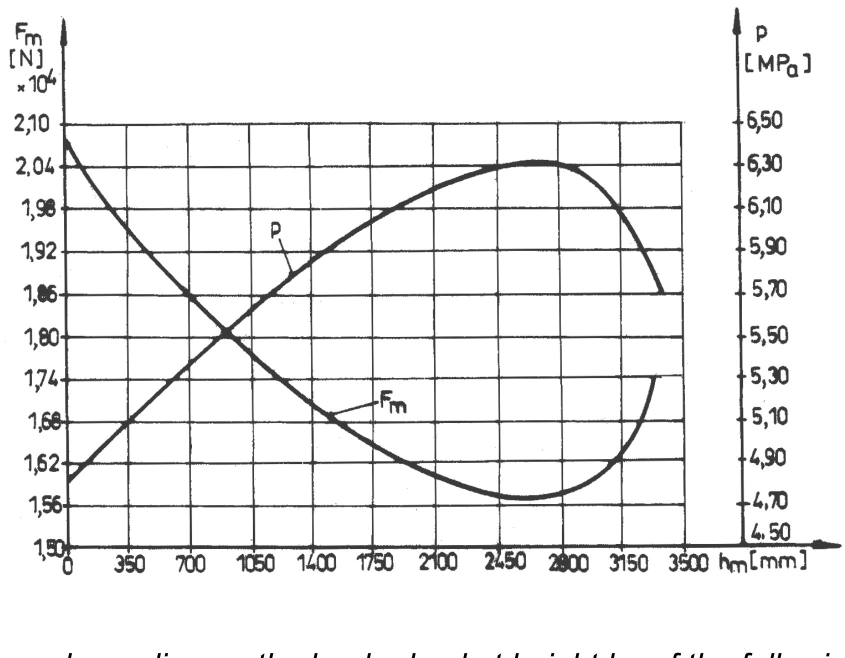

Fig. 8. Variations depending on the loader bucket height h_m of the following parameters:
a – cylinder pressure p (for F_m = const);
b- force acting upon the bucket F_m (for p = const)

Considering that the force F_z developed (jointly) by the two hydraulic cylinders is given by the expression $F_Z = p\cdot \pi \cdot D^2/2$ (where D is the cylinder diameter and p – the pressure of the fluid in the cylinders), the variation of force F_m at a given pressure p (p = const) and the variation of pressure p in the hydraulic cylinder for a given force F_m (constant) depending on the height h_m of the bucket for the IF – 65 front loader (D = 80 mm) are plotted in figure 8.

CONCLUSIONS

- The front loaders mounted on agricultural wheel tractors are increasingly employed for the mechanization of material loading and unloading operations into/from transport means or other locations.
- The constructive and functional parameters of front loaders have to satisfy the requirements of the working process and have to correspond to the structures of the tractors they are mounted on.
- The agreement between the functional and constructive parameters of the front loader and of the tractor can be analysed based on mathematical models, which describe the kinematics and dynamics of the front loader. Further, computer simulation allows the establishing of the constructive and functional elements of the joining points of the loader arms and of the driving cylinder on the tractor body.

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