CONTRIBUTIONS TO THE STUDY OF THE DYNAMICS OF AGRICULTURAL TRACTORS EQUIPPED WITH FRONT-END LOADER AND REAR FORKLIFT LOADER

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Abstract. In the paper is analysed the longitudinal stability of tractor-front end loader system and of tractor- the forklift system in the most difficult work situations: descending on a slope, braking in translatory motion and acceleration of the fork while lifting the load. Based on the equivalent dynamical models of the real tractor-loader systems are elaborated the mathematical models describing the dynamical behaviour of the systems under working and transportation conditions, which deliver the criteria for the dynamic stability. Further, computer simulation allows the study of the longitudinal stability of the systems trough application for the constructive tractor-loader models.

Keywords: agricultural tractor, front end loader, forklift loader, dynamic model, mathematical model, overturning stability.

Introduction

The loaders mounted at the front-end of agricultural wheel tractors represent cost effective loading – unloading equipment, meant for loading operations of both lose grained material (earth, sand, garbage, seeds, fodder) and compact material (wrapped, on pallets or in containers). Front loaders on tractors are used for both loading – unloading operations in agriculture as well as in other fields (municipal engineering, forestry, building sites) using in this sense corresponding working organs (buckets of various forms, forks, pallets, blades, hooks etc.) [1, 2]. The manipulation of both pallets and box-pallets in agriculture farms can be performed on the relatively short distances (within a hangar or between close locations) and on the vertical up to certain heights, using the forklift equipment mounted on the tractor rear hitch [3].

The constructive and functional parameters of front and rear loaders mounted on agricultural wheel tractors have to satisfy the requirements of the working process and of the dynamic stability and have to correspond to the structures of the tractors they are mounted on.

Material and methods

1. Dynamic stability of tractor – front end loader system

During traveling between the loading and the unloading place, the tractor- front end loader systems are frequently subjected to braking processes, which under certain circumstances may cause the loss of longitudinal stability, by overturning round the front axle. The diagram of Figure 1 considers the most difficult situation in regard of stability, when the system is braked with deceleration during descending a longitudinal slope, at the same time with the braking of the charge during the lowering process (when inertia force acts upon the charge Q).

The exterior forces acting upon the system consisting of the tractor and the front loader with the filled bucket raised into transport position (height h_m) are as described in figure 1: G_t – own weight of the tractor; Q – total load of the working component (bucket); G_c – weight of the counterweight mounted at the rear of the tractor(including own weight of the loader arm and the weight of the empty working component); Z_1 and Z_2 – loads on the front and rear axle, respectively; F_f – total braking force developed on the braked wheels of the tractor (achieved by the adherence of the wheels to the road surface); R_r – total rolling resistance of the tractor wheels. The weights G_t, Q and G_c, are located in the mass centres of the respective components and are identified by the longitudinal and normal coordinates indicated in figure 1 (distance L represents the wheel base of the tractor).

Due to the braking of the tractor the force F_f is developed on the tractor wheels, and therefore the system is subjected to inertia forces generated by the deceleration d, forces parallel to the road surface and placed in the mass centres of the tractor body $G_{ti} = d \cdot G_t \cdot g^{-1}$), counterweight $G_{ci} = d \cdot G_c \cdot g^{-1}$, and load $Q_{ix} = d \cdot Q \cdot g^{-1}$, respectively. During braking of charge Q while lowering, corresponding inertia forces $Q_{iz} = Q \cdot a_q$ upon the fork, generated by the deceleration a_q.

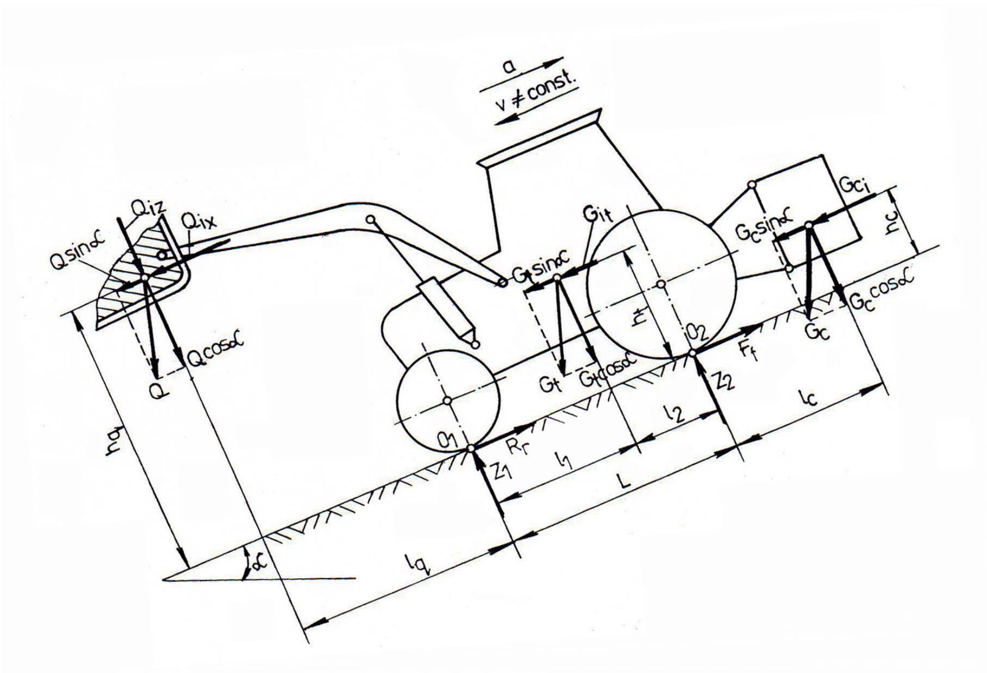

Fig.1. **Exterior forces acting upon the tractor-front loader system during downhill braking**

The total braking force F_f developed on the tractor wheels by the adherence to the road surface depends on the actuating mode of the brakes. In the case of four-wheel drive (4WD) tractors the wheels of both tractor axles are braked (integral braking) and, therefore, the maximum braking force is given by the relation ship: $F_{fmax}= \varphi(Z_1+Z_2)$, where φ is the adherence coefficient of the wheels to the road surface. In the case of rear driven tractors (4x2), only the rear axle wheels are braked (with normal load Z_2, so that the maximum braking force has the value: $F_{fmax}= \varphi Z_2$.

Due to the small values of the rolling resistance coefficients f compared to those of the adherence coefficient φ, the rolling resistance R_r can be neglected (i.e. $R_r = 0$).

From the equation of equilibrium of the system in traveling direction the braking force F_f is expressed by equation:

$$F_f = (G_t + Q + G_c)\left[\sin\alpha + (d/g)\right]. \tag{1}$$

The normal loads Z_1 and Z_2 on the front and rear axle of the tractor follow from the equilibrium equations of the equivalent dynamic model of figure 1, and are given by the following expressions:

$$Z_1 = \frac{\left[G_t l_2 + G_c l_c + Q.(L + l_q)\right]\cos\alpha}{L} + \frac{(G_t h_t + G_c h_c + Q.h_q)\sin\alpha}{L} + \frac{(G_t h_t + G_c h_c + Q.h_q).d + Q.l_q.a_q}{L.g};(2)$$

$$Z_2 = \frac{\left[G_t l_1 - G_c(L + l_c) - Q.l_q\right]\cos\alpha}{L} - \frac{(G_t h_t + G_c h_c + Q.h_q)\sin\alpha}{L} - \frac{(G_t h_t + G_c h_c + Q.h_q).d + Q.l_q.a_q}{L.g}. \tag{3}$$

The longitudinal overturning stability of the system for various values of the slope tilt angle α and the braking deceleration d is ensured if the tractor is counterweighted by a minimum weight $G_{c.min}$, determined from equation (3) by condition $Z_2 = 0$, wherefrom follows:

$$G_{c.\min} = \frac{G_t\left[h_t(\sin\alpha + d/g) - l_1\cos\alpha\right] + Q.[h_q(\sin\alpha + d/g) + l_q\cos\alpha]}{(L + l_c)\cos\alpha - h_c(\sin\alpha + d/g)}\ . \tag{4}$$

The value of the maximum deceleration d_{max} for which the longitudinal overturning stability is ensured is determined from equation (3) by condition $Z_2 = 0$. Solving the equation in function of deceleration d yields the expression of the maximum admissible braking deceleration for traveling conditions is expressed by equation:

$$d_{\max} = g.\frac{\lfloor G_t.l_1 + G_c(L + l_c) - Q.l_q \rfloor \cos\alpha - (G_t h_t + G_c h_c + Qh_q).\sin\alpha}{G_t h_t + G_c h_c + Qh_q}. \quad (5)$$

For maximum intensity braking the maximum deceleration d_{max} depends on the load on the braked wheels and the adherence coefficient to the road φ. For 4 WD tractors braking is carried out on both axles (integral braking), so that the maximum braking force will be: $F_{fmax}= \varphi(Z_1+Z_2)$. Considering equations (2) and (3) the maximum achievable value of the deceleration d_{max} is given by equation:

$$d_{max} = g\ (\varphi \cos\ \alpha - \sin\alpha). \quad (6)$$

For rear driven tractors (2WD tractors) with barking of the rear wheels only, the maximum braking force is $F_{fmax}= \varphi\ Z_2$. Considering equations (2) and (3), the maximum achievable value of the deceleration d_{max} is given by equation:

$$d_{\max} = g.\varphi.\frac{\lfloor G_t l_1 - G_c(L + l_c) - Q.l_q \rfloor \cos\alpha - (G_t h_t + G_c h_c + Q.h_q)\sin\alpha - L(G_t + G_c + Q)\sin\alpha}{L(G_t + G_c + Q) + \varphi.(G_t h_t + G_c h_c + Q.h_q)}. \quad (7)$$

2. Dynamic stability of tractor- fork lift system

The diagram of figure 2 considers the most difficult situation in regard of stability, when the system is braked with deceleration a during descending a longitudinal slope, at the same time with the braking of the charge Q during the lowering process with deceleration a_q (when inertia force Q_{iz} acts upon the charge). The significance of the notations in the figure 2 is the one mentioned for the system shown in figure1. The weight Q includes both the material weight and the own weight of the lifting equipment**.**

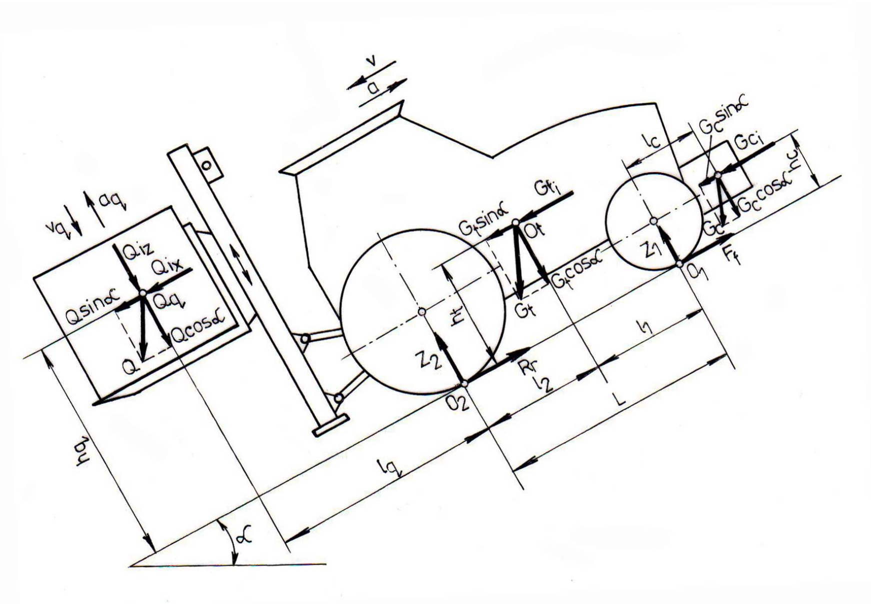

Fig. 2. **External forces acting upon the on the forklift truck during braking on a longitudinal descending slope**

The normal load Z_1 on the front axle of the braked forklift with deceleration d during descending a slope tilted by angle α, follow from the equilibrium equations of the simplified equivalent dynamic model of figure 2, and is given by the following expression:

$$Z_1 = \frac{\lfloor G_t l_2 - G_c(L + l_c) - Q.l_q \rfloor \cos\alpha}{L} - \frac{(G_t h_t + G_c h_c + Q.h_q).\sin\alpha}{L} - \frac{(G_t h_t + G_c h_c + Q.h_q).d + Q.l_q.a_q}{L.g}. \quad (8)$$

The system loses its longitudinal stability (overturns round the rear axle) when the load on the front axle Z_1 becomes zero (Z_1 = 0). Condition Z_1 = 0 in equation (8) allows establishing of the maximum (critical) value of the tilt angle α_{max}, or of the braking decelerations of the truck a or of the braking decelerations a_q of the load Q which the system loses its dynamic longitudinal stability .

To ensure manoeuvrability, at least 20 % of the tractor weight G_t needs to remain on the front axle (which is the steering axle), that is $Z_{1min} = 0.2.G_t$. By imposing this condition, the maximum values of the slope angle α can be computed by the equation (8) that is the slope accessible to the vehicle traveling with various decelerations.

Another important aspect of the tractor - front loader system dynamics is the motion of the charged bucket on transversal slopes (Fig. 3).

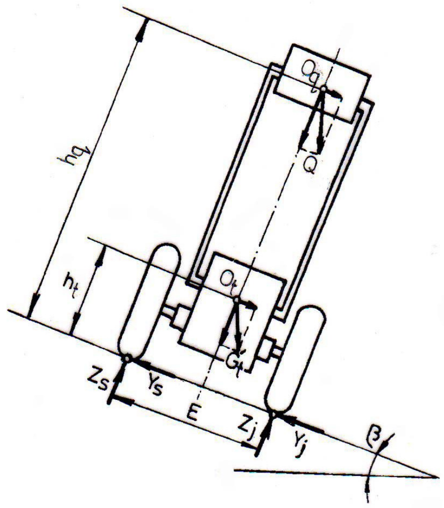

Fig. 3. **Forces acting on the tractor - loader system when moving on a transversally slope**

From the equilibrium equations of the system the normal reaction (perpendicular on the road surface) in the uphill Z_s is given by the expression:

$$Z_s = \frac{0.5E(G_t + Q)\cos\beta - (G_t h_t + Q.h_q)\sin\beta}{E}, \qquad (9)$$

where E – the wheel trade of the tractor;
β – transversally slope angle.

The stability to lateral turning over of the tractor – loader system is given by the condition $Z_s > 0$, wherefrom, following transformations the expression of the stability condition to lateral turning over follows:

$$tg\beta \le \frac{0.5E.(G_t + Q)}{G_t h_t + Q.h_q}. \qquad (10)$$

Results and discussion

The computer aided solving (simulation) of equation (3) allows the analysis of the variation of the rear axle loads Z_2 and implicitly the longitudinal stability of the tractor depending on the values of the descended slope tilt angle α and the braking deceleration d, considering the front loader bucket carrying various loads Q and raised to various heights h_q, plotted for the case of the system consisting of a wheel tractor U-650 M (made in Romania) with wheel base L = 2400 mm, weight G_t = 4000 N and coordinates l_2 = 952 mm; h_t = 1263 mm) equipped with an IF 65 front loader and counterweigt G_c = 8000 N for traveling with the bucket carrying the load Q =10000 N raised to transport height h_q = 2120 mm [2]. The graph presented in the figure 4 shows that for braking deceleration values of d = 2.5 m·s^{-2}, the longitudinal overturning of the system (Z_2 = 0) occurs for tilting angles of the slope of about α = 0.57 rad (α = 33°). For braking deceleration of d = 5.0 m·s^{-2} (achievable by 4 WD tractors during braking on flagstone or dry earth roads), the longitudinal overturning of the system occurs at much smaller tilting angles of the slope, of about α = 0.27 rad (α = 16°).

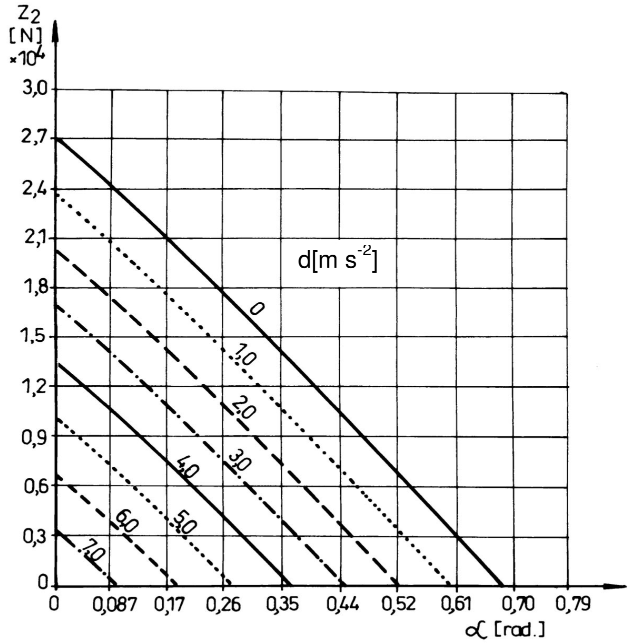

Fig. 4**. Variation of loads Z_2 on the tractor rear axle during downhill braking in dependence on the slope angle α, for various braking decelerations *d***

The braking adherence coefficient φ of the road depends on the road type and its state and has the values: φ = 0.70…0.75 – for dry concrete and asphalt; φ = 0.5…0.7 – for wet concrete and asphalt; φ = 0.5…0.6 – for flagstone roads; φ = 0.65- for dry earth roads; φ = 0.4…0.5 – for wet earth roads [4].

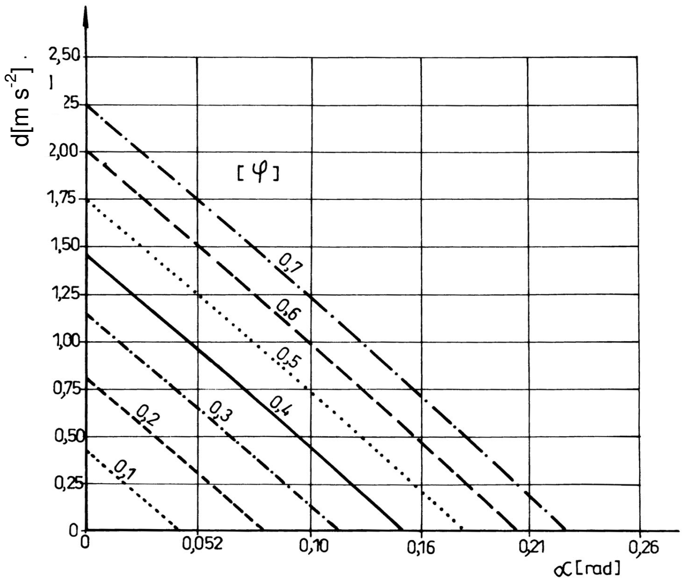

Fig. 5**. Variation of the maximum braking deceleration d_{max} achievable by the 2WD tractor U 650 M depending on the slope tilt angle and various adherence coefficients of the road φ**

Figure 5 presents a graph highlighting the variation of the maximum braking deceleration d_{max} depending on the values of the descended slope tilt angles α, for adherence coefficients of the road φ taking values between φ = 0... 0.7, during the braking of the system including the 2WD tractor U-650 M and the *IF 65* front loader [2]. The graph was obtained by computer simulation of equation (7) for the system traveling with a bucket carrying the rated load (Q = 10000 N) and raised to a medium height (h_q = 2120 mm). It can be noticed that for braking on surfaces of adherence φ = 0.7 (asphalt, concrete) and traveling on horizontal roads (α = 0°) the braking deceleration reaches values of about 2.25 m·s^{-2}. With an increasing tilt of the slope, the maximum braking deceleration d_{max} decreases significantly, reaching 1.25 m·s^{-2} for angles α = 6...7°, and tends towards zero for slopes of tilt angle α = 12…15°.

Conclusions

1. The front loaders mounted at the front-end of agricultural wheel tractors are increasingly employed for the mechanization of material loading and unloading operations into/from transport means or other locations on low and medium agricultural farms.
2. The manipulation of both pallets and box-pallets in agriculture farms can be performed on the relatively short distances (within a hangar or between close locations) and on the vertical up to certain heights, using the forklift equipment mounted on the tractor rear hitch.
3. The constructive and functional parameters of front and rear loaders mounted on agricultural wheel tractors have to satisfy the requirements of the working process and of the dynamic stability and have to correspond to the structures of the tractors they are mounted on.
4. The braking of the tractor equipped with a front and rear loaders during descending a longitudinal slope with the filled bucket or forklift in transport position are in relation to the longitudinal stability of the system the most difficult situation of the traveling process.
5. The dynamics of tractor – front end loader and fork lift loader systems can be analyzed by mathematical modeling of the equivalent dynamic models of the real systems, taking into account the exterior forces to which they are subjected in various working situations.
6. Based on the equivalent dynamical models of tractor – front end loader and fork lift loader systems it can be elaborated the mathematical model describing the dynamical behaviour of the forklift truck during the descending on a slope by slowing down (breaking) of the vehicle and acceleration of the fork while lifting the load.
7. The mathematical models tractor –loader systems allow the analysis of the overturning stability of the systems, for various concrete working and traveling conditions. The mathematical models deliver the criteria for the overturning stability.

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