CONTRIBUTIONS TO THEORTICAL AND EXPERIMENTAL STUDY OF THE DYNAMIC STABILITY OF THE FORKLIFT TRUCKS

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Abstract: The first part of the paper presents the equivalent dynamical model of the forklift system in the most difficult work situations: descending on a slope braking of the vehicle in translational motion and acceleration of the fork while lifting the load. Based on the dynamical model are elaborated the mathematical models describing the dynamical behavior of the forklift truck during moving or working. These models deliver the criteria for the overturning stability. The last section of the paper presents a measurement installation developed for experimental research on the dynamics of the fork lift truck.

Keywords: forklift truck; dynamical model; mathematical model; longitudinal stability, experimental research

1. INTRODUCTION

The complete mechanization of the manipulation of various products with the same equipment is based on applying pelleting technology, which involves the placing of wrapped products on international standard size platforms, known as pallets. The manipulation of both pallets and box-pallets is mechanized and can be performed on the horizontal on relatively short distances (within a hangar or between close locations) and on the vertical up to certain heights, using the same type of equipment, as described in Figure 1, called forklift trucks. The constructive and functional parameters are generally the following: the nominal (rated) charge to be lifted, the maximum lifting height, the constructive height, the free height, the position of the mass center in relation to the supporting polygon and the stability characteristic.

The nominal/rated lifting charge represents the maximum charge or load that can be lifted by a motor forklift truck to the maximum height reachable by the forks, and generally varies between 500 and 5000 kg. *The maximum lifting height* varies between 1600…10000 mm. Forklift trucks working in storage rooms of 8 m height, need to allow a minimum lifting height of 5600 mm. For low height (up to 5 m) storage rooms, forklift truck lifting height needs to be of at least 3200 mm. *The constructive height* of the forklift truck is conditioned by the height of the gates it has to pass, and varies between 600…1800 mm for railway car forklift trucks and does not exceed 2250 mm for storage room ones. *The free height* represents the point to which the load can be lifted without modifying the constructive height of the truck. For storage room trucks this height needs to be of at least 3000 mm, while for railway car ones the minimum value is of at least 1250 mm. *The stability characteristic* is generally presented as a diagram, where the abscissa features the values for the distance between the mass centers of the load to the fork bead (called mass center height), while the ordinate shows the values of the load. This diagram allows the selection of the type of forklift truck depending on the mass of the manipulated load and on its plane dimensions (pallet dimensions).

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2. DYNAMICS OF LONGITUDINAL STABILITY OF THE FORKLIFT TRUCK

During travelling between the loading and the unloading place, the forklift 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, is when the system is braked during descending a longitudinal slope, at the same time with the braking of the charge during the lifting - lowering process (when inertia force acts upon the charge *Q*) [1].

The exterior forces acting upon the system during braking on a longitudinal descending slope (tilted by angle α) with the center of gravity of the load *Q* lifted to height h_q are as described in Figure 1: *G* is the own weight of the vehicle empty ; *Q* – load of the charged working component (fork); Z_1 and Z_2 - loads on the front and rear axle, respectively; F_f - braking force developed on the vehicle wheels; $R_{r1} = f \cdot Z_1$ and $R_{r2} = f \cdot Z_2$ – rolling resistances of the front and rear axle wheels respectively (where *f* is the rolling resistance coefficient of the vehicle wheels).

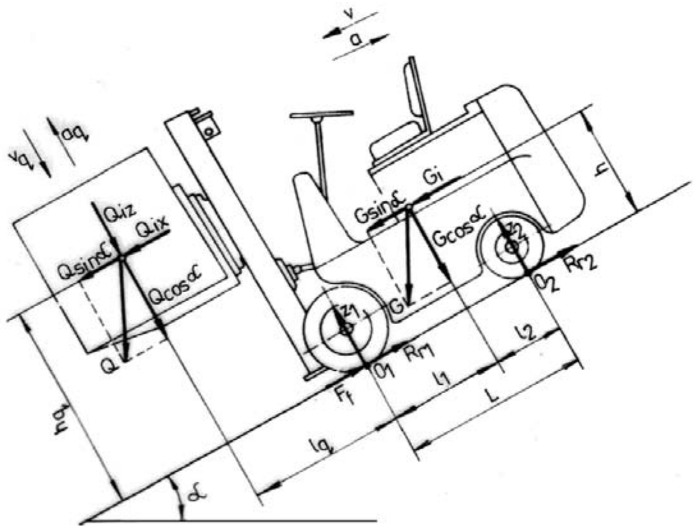

Fig. 1. External forces acting upon the on the forklift truck during braking on a longitudinal descending slope.

Due to the braking force F_f developed on the vehicle wheels, the system body is subjected to inertia forces generated by the deceleration *a,* forces parallel to the road surface and placed in the mass centers of the vehicle body: $G_i = a \cdot G/g$ and charge $Q_{ix} = a \cdot Q/g$, respectively. During descending the slope, the same masses are subjected also to the components parallel to the road surface of the weights of these masses: $G \cdot \sin\alpha$ and $Q \cdot \sin\alpha$, placed in the centers of gravity of these masses. During braking of charge Q while lifting or lowering, corresponding inertia forces act upon the fork, opposed to the acceleration a_q: $Q_{iz} = a_q \cdot Q/g$.

The total braking force F_f developed on the track wheels by the adherence to the road surface depends on the actuating mode of the brakes. The maximum braking forces given by the relationship: $F_{fmax} = \varphi \cdot (Z_1 + Z_2)$, where φ is the adherence coefficient of the wheels to the road surface [2, 3]. 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. $R_r = R_{r1} + R_{r2} = 0$), wherefrom follows: $F_f = (G + Q) \cdot [\sin\alpha + (a/g)]$.

The normal loads Z_1 and Z_2 on the front and rear axle of the tractor braked with deceleration *a* during descending a slope tilted by angle α, follow from the equilibrium equations of the simplified equivalent dynamic model of Figure 1, and are given by the following expressions:

$$Z_1 = \frac{\left[G \cdot (L - l_1) + Q \cdot (L + l_q)\right] \cdot \cos\alpha}{L} + \frac{\left(G \cdot h + Q \cdot h_q\right) \cdot \sin\alpha}{L} + \frac{a \cdot \left(G \cdot h + Q \cdot h_q\right) + a_q \cdot Q \cdot l_q}{g \cdot L}; \quad (1)$$

$$Z_2 = \frac{\left(G \cdot l_1 - Q \cdot l_q\right) \cdot \cos\alpha}{L} - \frac{\left(G \cdot h + Q \cdot h_q\right) \cdot \sin\alpha}{L} - \frac{a \cdot \left(G \cdot h + Q \cdot h_q\right) + a_q \cdot Q \cdot l_q}{g \cdot L}. \quad (2)$$

From the above equations follows that the inertia forces generated by the braking deceleration a and the system weight components parallel with the traveling direction cause an unloading of the vehicle rear axle Z_2 at the same time with the loading by the same value Z_1 of the front axle; this process is intensified with an increasing tilt angle α and the braking decelerations of the truck a and of the load a_q.

The most frequent situation in practice is that of the forklift in braked downhill motion with the fork charged with the nominal load Q and fixed in transport position h_q. As $a_q = 0$, the load on the rear axle, Z_2, is given by the following equation:

$$Z_2 = \frac{\left(G \cdot l_1 - Q \cdot l_q\right) \cdot \cos\alpha}{L} - \frac{\left(G \cdot h + Q \cdot h_q\right) \cdot \sin\alpha}{L} - \frac{a \cdot \left(G \cdot h + Q \cdot h_q\right)}{g \cdot L}. \quad (3)$$

In lifting – lowering operations conducted with an acceleration a_q of the fork charged with load Q, and the forklift resting (braked) on a downhill slope ($a = 0$), the load on the rear axle, Z_2, is given by the equation:

$$Z_2 = \frac{\left(G \cdot l_1 - Q \cdot l_q\right) \cdot \cos\alpha}{L} - \frac{\left(G \cdot h + Q \cdot h_q\right) \cdot \sin\alpha}{L} - \frac{a_q \cdot Q \cdot l_q}{g \cdot L} \quad (4)$$

The system loses its longitudinal stability (overturns round the front axle) when the load on the rear axle Z_2 becomes zero ($Z_2 = 0$). Condition $Z_2 = 0$ in equations (3), (4) and (5) allows establishing of the maximum (critical) value of the tilt angle α_{max}, the maximum braking decelerations a_{max} of the truck or the maximum braking deceleration a_q of the load Q which the system loses its dynamic longitudinal stability.

In braking on a downhill slope with the fork charged and fixed ($a_q = 0$) lifted into transport position, the maximum admissible acceleration a_{max} following from the condition of longitudinal overturning stability ($Z_2 = 0$ in equation (3)) of the forklift is:

$$a_{\max} = g \cdot \frac{\left[G \cdot l_1 - Q \cdot l_q\right] \cdot \cos\alpha - \left(G \cdot h_t + Q \cdot h_q\right) \cdot \sin\alpha}{G \cdot h_t + Q \cdot h_q}. \quad (5)$$

In braked resting on a downhill slope ($a = 0$) the maximum admissible acceleration a_{qmax} of the fork in lifting-lowering operations following from the conditions of longitudinal overturning stability ($Z_2 = 0$ in equation (4)) of the forklift is:

$$a_{q\max} = g \cdot \frac{\left[G \cdot l_1 - Q \cdot l_q\right] \cdot \cos\alpha - \left(G \cdot h + Q \cdot h_q\right) \cdot \sin\alpha}{Q \cdot h_q}. \quad (6)$$

In the same time to ensure maneuverability of the vehicle, at least 20% of the vehicle weight needs to remain on the rear axle (which is the directing axle), that is $Z_{2min} = 0.2\ G$ [2, 3]. By imposing this condition $Z_{2min} = 0.2\ G$, the maximum values of the slope angle α_{max} and accelerations a_{max} and a_{qmax} can be computed by the equation below.

Analysis of the analytical relationships (mathematical models) reveals that increasing the angle of the downhill slope, increasing braking intensity (increasing braking deceleration), increasing the load of the fork, increasing the transport height of the load on the fork and increasing the lifting acceleration of the charged fork cause a decrease in longitudinal overturning stability (maneuverability) of the moving system, going as far as complete loss of stability. Analysis is achievable by computer aided simulation and plotting of the corresponding graphs.

3. EXPERIMENTAL RESEARCHES

The technical characteristics of the forklift deployed for experimental field tests include: deadweight/empty weight (unloaded fork) m = 4550 kg (with m_1 = 2260 kg on the front axle and m_2 =2290 kg on the rear axle); wheelbase L =1.830 m; coordinates of the mass center: distance on the horizontal x_c = 0.91 m (in relation to the rear axle) and height z_c = 0.65m (in relation to the supporting surface). These data were determined by measurements and were used in theoretical research for the mathematical models (computer simulation). The forklift has a driving front axle and a steering rear axle (turnable wheels actuated via the steering wheel). The braking system only operates only on the front wheels.

The objectives of experimental research consisted mainly of establishing via measurements the simultaneous variation in time of the rear axle load Z_2 and the braking deceleration a of the forklift, in order to analyze the longitudinal overturning and moving stability (maneuverability) of the system under various conditions, and to verify the results of theoretical research by computer aided simulation of the devised mathematical models. Thus the accuracy of dynamic modeling developed as part of the theoretical study can be improved and eventually validated.

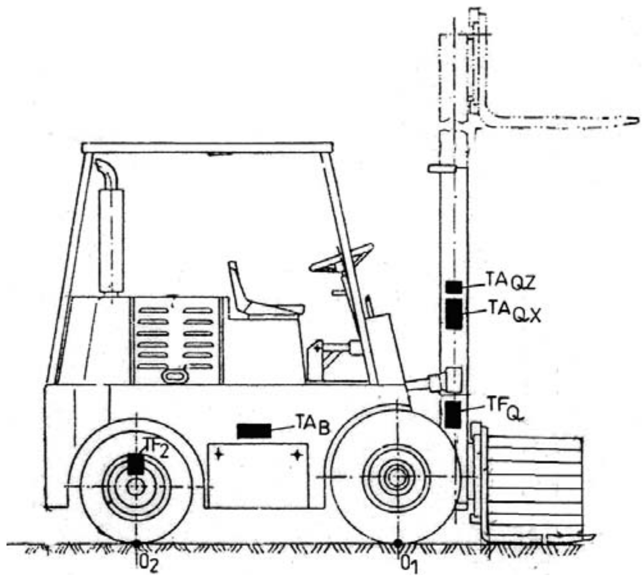

Fig. 2. Transducers and sensors mounting diagram on the fork lift truck system:
TF_Q - transducer for measuring the force in the fork lifting hydraulic cylinder rod (dynamic load of the fork); TA_{Qz} - transducer for measuring fork acceleration on vertical direction; TA_{Qx} - transducer for measuring fork acceleration on horizontal direction; during the forklift motion; TA_B - transducer for measuring horizontal acceleration (implicitly the speed and displacement); TF_2 - transducer for measuring dynamic load on the rear axle (steering axle).

The experimental research was done in different displacement conditions of the forklift, by accelerating to various speeds (3, 6, 10 km/h) and followed by braking until full stop, having the fork loaded with different weights (0, 600, 1200, 1800) placed at different lifting heights above the ground (0, 0.2 and 0.5 m). Before performing the displacement tests was determined the position of the center of mass (height from the ground and distance to the axles) for various loads upon the fork and also different heights above the ground. In order to carry out experimental research on the longitudinal stability of the forklift truck a modern measurement installation for recording and processing of data collected by sensors was developed, which allowed the simultaneous measurement of follows parameters: the rear axle loads, the load acting upon the fork, the horizontal velocity and acceleration of the truck body and the vertical and horizontal acceleration of the charged fork. The location of measuring transducers on the machine is presented in Figure 2.

Figure 3 presents the schematic of principle of the measurement, data acquisition and processing equipment The measurement of the force acting upon the fork lifting hydraulic cylinder rod, that represents the dynamic load acting upon the fork, was done indirectly by measuring the oil pressure in the fork lifting hydraulic cylinder. The measurement of the pressure was performed by help of a pressure transducer TF_Q (type P6A-Hottinger with inductive half-bridge) connected to the cylinder oil pipe. Measurement of the vertical and horizontal accelerations of the lifting fork was conducted by inductive acceleration transducers TA_{Qx} and TA_{Qz} with seismic masses (type B12/200-Hottinger, with inductive half-bridge). The dynamic load (pressure force) Z_2 on the rear (steering) axle of the forklift was measured by means electro-resistive transducers with strain gauges (of 120 Ω resistance) mounted in pairs on the arms of the rear axle. The force transducer of the axle was gauged and calibrated statically on horizontal ground by loading with known weights over the static load Z_{20} that presses on the axle in the absence of a charge on the fork [3]. The measurement of the horizontal acceleration and implicitly the speed of the forklift and distance covered by the forklift during tests were achieved by an optic transducer TA_B (type S 400) mounted laterally on the truck body at 400 mm height above the ground. The transducer was calibrated on the forklift while in motion.

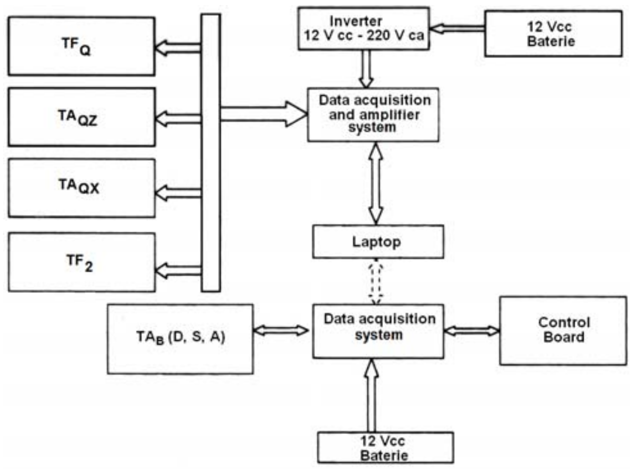

Fig. 3. Diagram of data acquisition and processing equipment.

The data acquisition and amplifier system is of MGC plus - Hottinger type. Feeding was ensured by a 12 V cc battery by means of a 1000 W dc/ac inverter with ac 220 V output voltages. The amplifier system allows the connecting of 16 modules. The measured data, recorded on a Toshiba Satellite Laptop were transmitted to a DAS3 type data acquisition system endowed with a DAS2 control board (6 analogical input channels and 6 fast counter inputs, and dc 9…26 V feeding voltage). Data were saved on a memory card.

Figures 4 and 5 exemplify graphs of the forklift tractor's rear axle load variation versus time (Figure 4) and of its velocity (Figure 5) in the case of intensive braking on paved horizontal ground with 1800 kg fork load lifted to 0.5 m height. It has to be pointed out, that in order to prevent a possible longitudinal turn-over (towards the front) of the forklift during intensive braking, experiments did not include loads exceeding 1800 kg nor lifted higher than 0.5 m.

The rear axle loads for large braking loads and great lifting heights were determined by computer simulation of the dynamic and mathematical models of the system for experimentally obtained values of deceleration. Processing of the experimental data revealed intensive braking accelerations on concrete pavement in the range of 2.2 … 2.75 m/s^2.

The experimental data confirmed from both qualitative and quantitative viewpoints the data obtained by theoretical studies, revealing that during braking the dynamic loads on the rear axle decrease, whilst increasing by the same amount on the front one. For certain values of the fork load and certain lifting heights, the load on the (steering) rear axle decreases under 20 % of the forklift tractor weight. Hence, as steering is ensured by the rear axle, forklift maneuverability (motion stability along the set trajectory) may be lost.

The situation becomes critical only when the rear axle load becomes zero, when the forklift loses its longitudinal stability (turns over front wise). A situation close to such a case occurs during the motion presented in Figure 4, where the real axle unload nearly reached the static load of 10830 N corresponding to a fork load of 1830 kg.

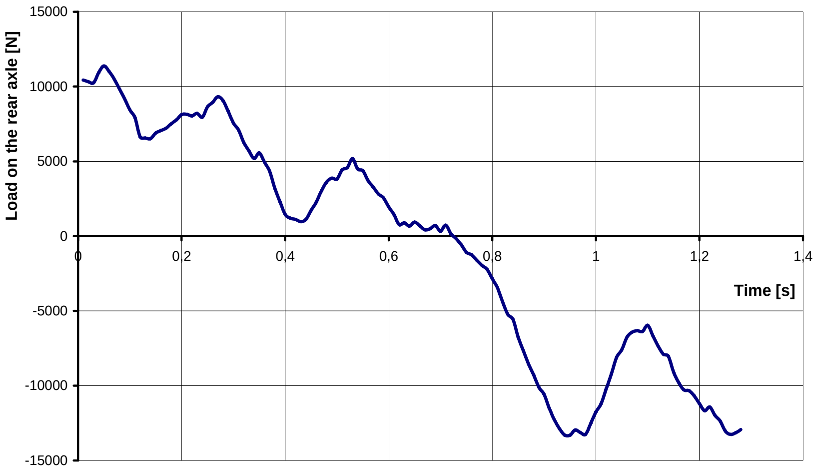

Fig. 4.Variation versus time of the forklift rear axle load in the case of intensive braking on horizontal ground (asphalt) with 1800 kg fork load lifted to 0.5 m height (initial vehicle speed: 10 km/h).

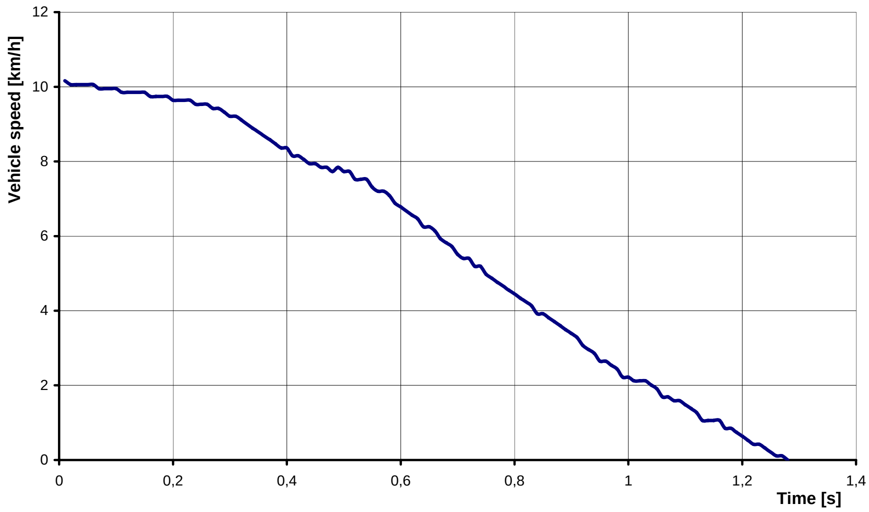

Fig. 5.Variation versus time of the forklift velocity in the case of intensive braking on horizontal ground (asphalt) with 1800 kg fork load lifted to 0.5 m height (initial vehicle speed: 10 km/h).

4. CONCLUSIONS

The braking of the forklift trucks during descending a longitudinal slope with the filled palettes or forklift in transport position is in relation to the longitudinal stability of the system the most difficult situation of the travelling process.

The dynamics of 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. Based on the equivalent dynamical models it can be elaborated the mathematical model describing the dynamical behavior during the descending on a slope by breaking of the vehicle and acceleration of the fork while lifting the load. The mathematical models deliver the criteria for the overturning stability. By computer simulation of the mathematical models the longitudinal stability of the forklift truck can be analyzed trough application in the constructive model of the fork lift truck parameters and travel and work conditions.

The experimental analysis of system behavior related to longitudinal overturning stability and maneuverability under various conditions requires the simultaneous determination of the rear axle load variation and the braking deceleration of the forklift. Further required is determining the variation of forklift acceleration/deceleration in lifting/lowering of the load.

By comparing the results of theoretical research obtained by mathematical model based simulation with the experimental, measurement-based ones, the accuracy of dynamic and mathematical modeling of the real physical models of forklifts can be verified in view of their improvement, such as to obtain simulation-based theoretical results as close as possible to experimental ones.

Developing dynamic and mathematical models able to replace real systems and situations allows the simulation of system dynamic behavior by means on dynamic and mathematical modeling and thus partial replacement of cost and time intensive, in overturning limit situations even dangerous experimental research.

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