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MODELLING FORKLIFT TRUCK MOVEMENT IN THE VDI CYCLE AND THE POSSIBILITY OF ENERGY RECOVERY

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Abstract: *This paper puts forward a proposal of description of movement of a forklift truck in the form of a non-linear differential equation. In this model, resistance to motion while driving in a straight line and along curves is taken into account. The external traction characteristics of a drivetrain are calculated on the basis of power of traction motors and static forces acting on the driving axle of a forklift truck, for an empty and loaded forklift truck. A model designed in such a way is used to carry out a simulation of forklift truck operation in a specified cycle defined by the VDI 2198 standard. This standard makes it possible to compare operating parameters of various forklift trucks under identical operating conditions. In the paper's conclusions, the amounts of possibly recoverable energy, coming from braking and lowering loads collected from racks by means of fork of a forklift truck, are estimated.*

Keywords: Forklift trucks, Modelling, Logistics warehouse systems.

1. Introduction

Similarly to other branches of industry and economy, modern logistics engineering searches for new technical solutions connected with moving goods in transport processes. In this search, we pay particular attention to ecological aspects and energy consumption. In modern drive system solutions, we strive to recuperate energy. These actions are part of global efforts to reduce energy consumption. Due to ecology and convenience, more and more internal combustion drives are replaced with electric drives. Such tendencies have been present in railway engineering and in the automotive industry for a long time, but also in industrial vehicles' drives paper Kwasniowski e al. (2008). Hybrid drives (internal combustion and electric with electric transmissions) have also become part of this trend. Research into energy consumption makes it possible to implement latest technologies and recuperate energy. Energy recovery is also employed in forklift trucks which are the subject of this paper. Energy recovery makes sense in machines in which the operating cycle involves frequent acceleration and braking of masses. Currently, we usually recover energy from the process of braking. Forklift truck's operation consists in constant accelerating and braking which provides a basis for closer investigation of those processes in terms of energy-efficiency. First energy recovery solutions have emerged in underground, light railway, trams, trolley buses, electric buses, diggers and forklift trucks. The key is to answer the question under what conditions one can recover energy using the results of a computer simulation of the operating cycle of a vehicle or a device and to what extent such a simulation corresponds to real operating conditions. In technical solutions, there has been a difficulty in accumulating recovered energy thus far. The answers to these questions can be obtained by way of modelling forklift truck's movement, taking into account the specifics of their motion. This paper Kwasniowski et al. (2011) presents a computational model of movement of a forklift truck in the form of a non-linear differential equation (taking resistance to motion and non-linear characteristics of a drive system under consideration). This tool allows calculating recoverable energy streams as a results of processes of braking and lowering loads from high racks using forklift trucks.

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2. Model of movement of a forklift truck

The movement of a forklift truck as a concentrated mass in accordance with Newton's second law of motion is the paper Zajac (2015):

$$\xi * m\frac{dV}{dt} + W_t = F_N \quad (1)$$

where: ξ – rotating masses coefficient ($\xi = 1.05$ – it takes into account the rotating parts of the forklift truck's drive system which affect its total kinetic energy. In forklift trucks, only wheels, traction motors and driveshafts are rotating parts. These parts accumulate a relatively small amount of energy in the rotational motion compared to the kinetic energy of translational masses. In this paper, a coefficient, which increases the substitute mass of a forklift truck by the effects of rotating masses, was set at 5 % of energy contained in the translational masses.) m – forklift truck's translational mass, Wt – rolling resistance (as a total value which varies as a function of the nature of linear or curvilinear motion), FN – maximum driving force (resulting from the external characteristics of the drive system – it depends on the speed of motion), Δt – time increment, Δs – distance increment along the test section, $V_{śr}$ – average speed. Rearranging the above equation, one can obtain the formula for forklift truck's distance increment:

$$\xi * \frac{G}{g} * \frac{dV}{dt} = F_N - W_t \quad (2)$$

$$\frac{\xi}{g} * \frac{dV}{dt} = \frac{F_N - W_t}{G} \quad (3)$$

$$\frac{\xi}{g} * \frac{dV}{dt} = p(v) \quad (4)$$

The following have to be substituted: $dV = \Delta V, dt = \Delta t, dt = \frac{\Delta s}{V_{śr}}$

$$\frac{\xi}{g} * \frac{\Delta V}{\Delta t} * V_{śr} = p(v) \quad (5)$$

$$\Delta s = \frac{\xi}{g} * \frac{\Delta V}{p(V)} * V_{śr} \quad (6)$$

where: Δs – distance increment along a given section, ξ – rotating masses coefficient ($\xi = 1.05$), g – gravitational acceleration ($g = 9.81\frac{m}{s^2}$), ΔV – speed increment along a given section, $p(V)$ – unitary accelerating ($p_N(V)$) / decelerating ($p_H(V)$) force per unit mass of the vehicle, $V_{śr}$ – average speed. The work performed is defined by the following formula:

$$\Delta W = F_N * \Delta s \quad (7)$$

where: ΔW – work increment, F_N – forklift truck's driving force, Δs – distance increment. The travel time can be determined using the following formula:

$$\Delta t = \frac{\Delta s}{V_{śr}} \quad (8)$$

Δt – time increment along a given section, Δs – distance increment, $V_{śr}$ – average speed.

3. Forklift truck's movement cycle according VDI2198

In order to compare the energy consumption of various designs of forklift trucks, forklift truck's movement cycle described in the VDI 2198 standard is used. The said cycle was shown in Fig. 1.

In the discussion, it was assumed that the forklifts truck's curvilinear motion was performed at a speed of 0.25 m/s, whereas its acceleration in each stage was achieved using its full power (external characteristics of the drive system). In practice, due to cost constraints and safety, full performance (acceleration) of a forklift truck is usually not used during its operation. It was assumed that the forklift truck carried a load of 1000 kg.

A forklift truck placed in the starting position accelerates and goes in a straight line over a distance of approx. 28 m and then limits its speed to 0.25 m/s in order to make a turn and pulls up to a rack. The next stage involves lifting empty fork to a height of 2 m, pulling up to a load, lifting it and backing up with the load.

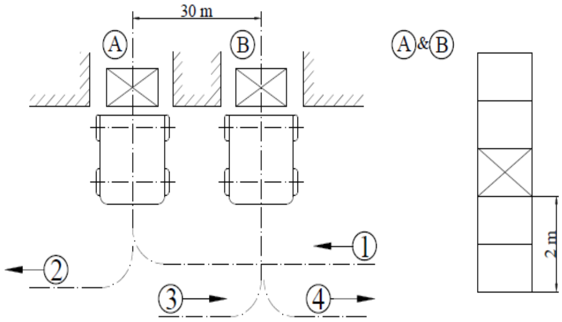

Fig. 1: VDI2198 cycle in the VDI2198.

Once the fork has been lowered, the next action involves backing up with the load and making a turn. Subsequently, after covering a straight stretch of road, the forklift truck makes a turn and then pulls up to rack B. The load is put back onto the rack at a height of 2 m and the empty forklift truck returns to its starting position in the papers Zajac (2011 and 2014 and 2015).

4. Results of simulation of forklift truck's movement

A simulation of movement of two forklift trucks was carried out: HYUNDAI 10/13/15BTR and Jungheinrich EFG-220. The evolution of changes in motion as a function of distance and time of covering individual phases of motion for both forklift trucks was shown in Fig. 2.

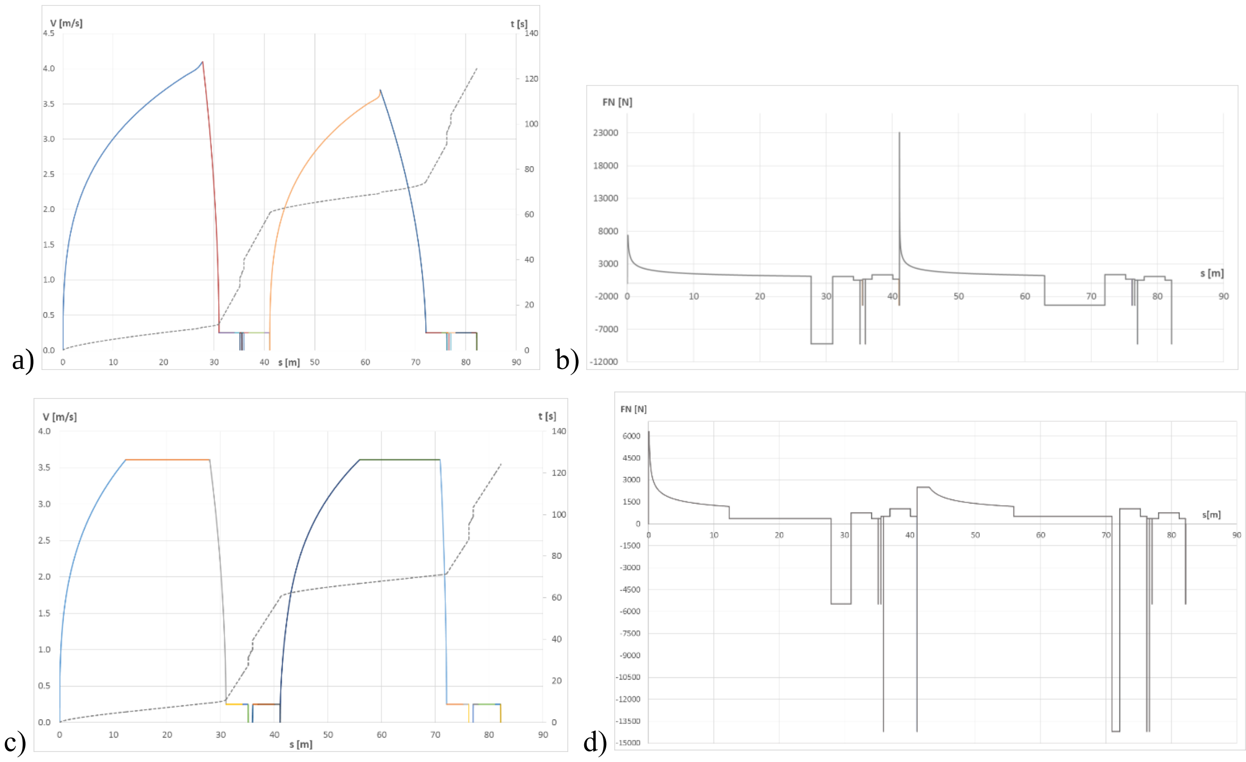

Fig. 2: Evolution of changes in motion as a function of distance and time of covering individual phases of motion: a), b) Run of Jungheinrich EFG 220 forklift truck; c), d) Hyundai 10/13/15BTR.

5. Conclusions

The results of simulation calculations made it possible to determine the total streams of energy in the investigated VDI operating cycle for both forklift trucks. They enable us to get to know better the advantages and disadvantages of both designs of forklift trucks with rear wheel drive (Hyundai 10/13/15BTR and Jungheinrich EFG-220). Important parameters of calculations in an operating cycle according to the VDI were summarised in Tab. 1.

The conducted simulation calculations of operation of forklift trucks indicated what theoretical streams of energy were recoverable in the processes of braking and lowering load masses. The calculations were carried out with the assumption that a forklift truck moved in accordance with the characteristics of its external drive system. In practice, this style of driving a forklift is used rather rarely. The process of recovery of energy of lowering a load on fork is in this case justified to a lesser extent. However, it should be borne in mind that the height of lowering assumed in the paper was just 2 metres. Recovering energy from the process of lowering loads is justified in cases of high rack stacker forklift trucks.

Tab. 1: Comparison of energy parameters of work of forklift trucks according to the VDI cycle (source: own work).

Parameter	Unit	Hyundai 10/13/15BTR	Jungheinrich EFG-220
Energy used up for movement E_j	kJ	73.6	356.8
Energy used up for lifting a load E_p	kJ	30.2	30.2
Forklift truck's braking energy E_h	kJ	34.4	54.9
E_p / E_j	%	41	8.5
E_p / E_j+E_p	%	21.2	7.8
E_j / E_j+E_p	%	70.9	92.2
E_h / E_j	%	46.7	15.4
$E_h / E_j + E_p$	%	33.1	14.2

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VDI2198 Standard.