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HYDRAULIC HYBRID VEHICLE
WITH ENERGY RECUPERATION

HYDRAULICZNY HYBRYDOWY POJAZD
Z ODZYSKIEM ENERGII

A b s t r a c t

Modern transport vehicles and mobile machines have a high advanced functionality and quality of work. However, it is often associated with high power consumption. That is why research focused on reducing vehicle operating costs is so important. The possibilities of reduction of fuel consumption in combustion engines, which are usually the primary source of energy in many vehicles, seem to be exhausted. It came from design constraints of the combustion engine and increasingly stricter emission's standards. That is way very popular become energy recovery system. Usually, these systems are based on an electric storage battery. Energy is capturing during braking of the vehicle and transferred to the electric motor periodically connected with the drive system. While, in the vehicles driven by hydrostatic system hydraulic energy in a similar way can be captured and stored in the hydro-pneumatic accumulator. This paper presents such solution of energy saving system based on an additional pump and hydro-pneumatic accumulator build into vehicle hydrostatic drive system. Mechanical and hydraulic elements of vehicle drive system were modelled using SimulationX software. The standard drive system is comparing with the energy recuperation drive system. Tests have been conducted for assumed working cycle and several operating parameters by the use of SimulationX. Reached than 10% energy saving in one cycle, confirms the correctness of designed structure of the hydraulic energy recovery system.

Keywords: Energy Recuperation, Hydrostatic Drive, SimulationX

S t r e s z c z e n i e

Współczesne pojazdy transportowe i maszyny mobilne charakteryzują się wysoko zaawansowaną funkcjonalnością i jakością pracy. Jest to jednak często związane z dużym zużyciem energii. Zrozumiałe jest zatem prowadzenie prac ukierunkowanych na ograniczenie kosztów eksploatacyjnych. Możliwość znaczącego obniżenia zużycia paliwa przez silniki spalinowe, będące zazwyczaj źródłem pierwotnym energii w pojazdach użytkowych, wydaje się być wyczerpana. Wynika to zarówno z ograniczeń konstrukcyjnych silnika spalinowego, jak i zaostrzających się norm dotyczących czystości spalin. Stąd też zainteresowanie systemami odzysku energii wspomagającej jednostkę napędową przy zwiększonym obciążeniu. Zwykle są to układy bazujące na akumulatorach elektrycznych, w których jest gromadzona energia przechwytywana w procesie hamowania pojazdu i przekazywana następnie do silnika elektrycznego łączonego okresowo z układem napędowym, nazywane popularnie hybrydowymi układami napędowymi. W artykule opisano rozwiązanie i wyniki testów symulacyjnych systemu odzysku energii kinematycznej dla małego pojazdu transportowego z przekładnią hydrostatyczną. Układ napędowy pojazdu złożony z elementów mechanicznych i hydraulicznych zamodelowano z wykorzystaniem bibliotek programu SimulationX firmy ITI GmbH. W celu porównania energochłonności standardowego układu napędowego i układu wspomaganego przez system rekuperacji energii przeprowadzono testy symulacyjne dla przyjętego cyklu roboczego oraz dla kilku konfiguracji parametrów eksploatacyjnych. Osiągnięta ponad 10% oszczędność energii w cyklu testowym potwierdza słuszność założeń zaprojektowanej struktury proponowanego systemu odzysku energii.

Słowa kluczowe: odzysk energii, napęd hydrostatyczny, SimulationX

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1. Introduction

We hope that this template will make it easier to write the article. In heavy-duty machines characterizing by a quasi-repeatable working cycle is the possibility to recover the kinetic and potential energy [2, 3, 7, 9, 10]. In mobile machines and vehicles are usually systems based on electric accumulators, which store energy captured during vehicle braking and next transmit energy to the electric motor that is periodically connecting with the drive system [4]. Such systems are commonly called hybrid powertrains. The problematic elements of this type of system are an electric accumulator. Due to the limited speed of chemical changes cannot accumulate large portions of energy in a short time and also have a limited number of charge cycles. Whereas, in vehicles with hydrostatic transmission can be used to capture and storage of energy hydro-pneumatic accumulator in a similar way as the electric accumulator [1].

2. The simulation model

The article describes the design and test results of simulation of kinetic energy recovery system for a small transport vehicle with hydrostatic transmission. Vehicle drive system composed of mechanical and hydraulic modelled using SimulationX ITI software.

Tests were conducted for assumed duty cycle and for several configurations of operating parameters to compare the energy consumption of the standard powertrain with a hydrostatic transmission system and powertrain aided by energy recuperation system simulation. In the mathematical model were made following assumptions:
- the wheeled vehicle is traveling on a flat, solid ground.
- no slip between the wheels and the ground,
- constant thermal conditions, the temperature of hydraulic oil changes much slower than changes in pressure,
- dynamics valves are omitted; response time is significantly shorter than time reaction of traveling mechanism.

The proposed solution of the secondary energy source in the form of a hydro-pneumatic accumulator such as Permo Drive system [8] used in trucks. In this system, a reversible hydraulic unit is mounted on the drive shaft of the vehicle, and the energy of the braking phase is stored in the hydro – pneumatic accumulators. The stored energy is redistributed to the reversible unit supporting the drive system during the acceleration phase of the vehicle. This solution is used as a support system for the classic drive system of the heavy transport vehicle [5, 6].

In order to reduce the cost of the components of the proposed system and the possibility of applying different control strategies already at the design stage, the recovery system combined with a mechanism for driving through a belt drive with toothed belt (9), controlled coupling (8) and additional pump (5) (Fig. 1). Installation of elements of the presented energy recuperation system (rectangular block – dashed line) does not require significant modifications of the standard hydrostatic transmission and does not change its basic functionality. The weight of additional elements depending on the final configuration and will be oscillated near several dozen kilos so that it will be had not an affect significantly on the capacity of tested transport vehicle. Complete vehicle kerb weight is 1000 kg.
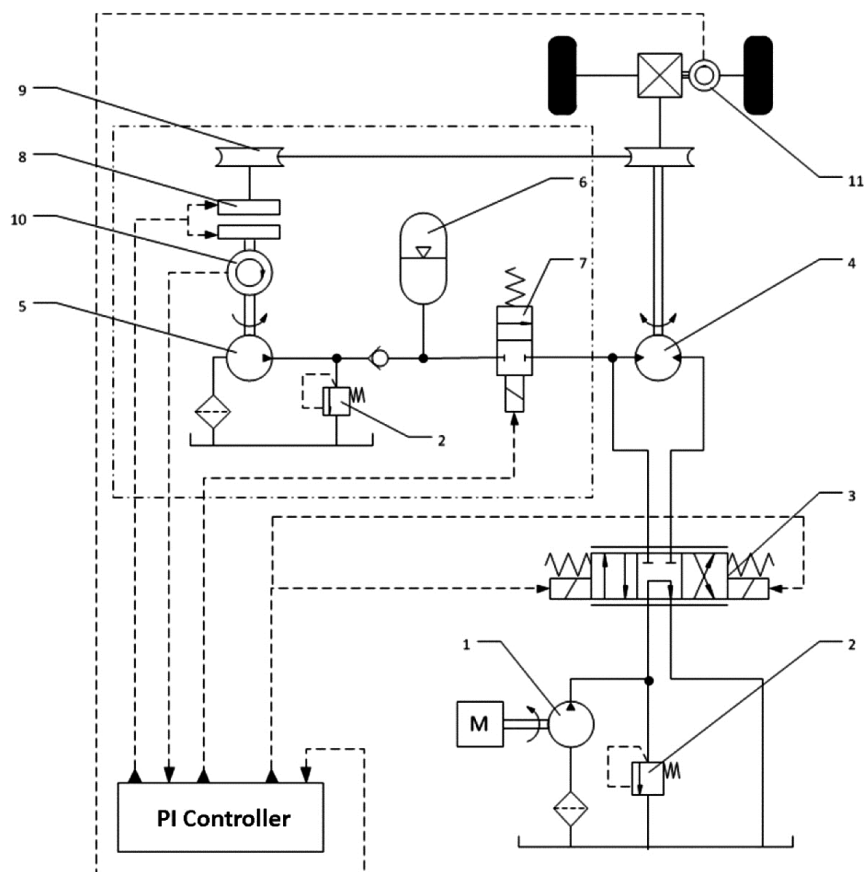
Fig. 1. Schema of hybrid (mechanical – hydraulic) hydrostatic drive system with Energy recuperation where: 1 – main pump, 2 – relief valve, 3 – 4/3 proportional directional valve, 4 – hydrostatic motor, 5 – additional pump, 6 – hydro – pneumatic accumulator, 7 – 2/2 directional valve, 8 – clutch, 9 – teeth belt transmission, 10,11 – rpm transducers

The controller based on signals from velocity sensors of additional pump shaft (5) and the vehicle drive axle generates control signals for proportional directional control valve (3), 2/2 valve on/off type (7) and switching actuator of disc clutch (8). The PI controller used in the controller provides repeatable vehicle traction parameters that are necessary for correct comparison the operating parameters of conventional and recuperation energy system. Working cycle selected for simulation tests consists of two vehicle speed test runs with a five – second acceleration phase, a thirty – five – second phase of constant travelling speed and the three – second deceleration phase. The simulation was carried out for three target speeds of the vehicle, i.e. 10, 15 and 25 km/h and in the consequence for three distances covered from 200 to 500 m. During testing of the system with energy recovery, the hydro – pneumatic accumulator was pre – charged to about 50% of the nominal volume and was not used in the first phase of acceleration of the vehicle. Next, in both periods of deceleration of

the vehicle, accumulator was charged. The additional pump was driven until the speed of the drive shaft in this unit does not decrease below 600 rpm (by reason of the low efficiency of the pump at a lower speed). Table 1 shows the data, taken for simulation and operating parameters shown at the graphs.

T a b l e 1

Summary of key physical quantities adopted for the simulation
and determined system parameters

Quantity	Symbol	Value/Unit
Complete vehicle kerb weight	m	1000÷2000 [kg]
the vehicle set speed	v	10÷25 [km/h]
belt transmission ratio	i	3
relief valve opening pressure	p_o	18 [MPa]
hydro-pneumatic accumulator nominal volume	V_{acc}	5÷40 [dm³]
hydro-pneumatic accumulator pre-fill pressure	p_{acc}	3.5 [MPa]
main pump displacement volume	q_1	18 [cm³/rev]
auxiliary pump displacement volume	q_2	30÷40 [cm³/rev]
the hydraulic motor displacement volume	q_s	100 [cm³/rev]
combustion engine power at 2000 rpm	N_s	24 [kW]
main pump outlet pressure	p_{p1}	[MPa]
auxiliary pump outlet pressure	p_{p2}	[MPa]
hydraulic motor inlet pressure	p_s	[MPa]
travelled distance	L	[m]
combustion engine power in classic system	N_s	[kW]
combustion engine power in system with energy recover	N_{acc}	[kW]

3. Simulation result

Fig. 2 shows selected working parameters of hydrostatic transmission with energy recuperation system.

In 50 and 120 seconds, the moment of the switching of the auxiliary pump during braking phase (pressure p_{p2} increased) is visible. The operation time of this unit is very short, so the hydro – pneumatic accumulator is loaded in 2 seconds cycles, which forced the pre – selection of the size of the additional pump. The pump displacement volume is 40 m³/rev.

Hydro-pneumatic accumulator model used in the simulation takes into consideration the thermodynamic losses. This effect is visible on the graph of hydro – pneumatic accumulator pressure p_{acc}. This pressure gradually decreases when the accumulator is not using and in this way reducing the efficiency of the proposed system. During vehicle acceleration in the second cycle, the system using the power from the hydro-pneumatic accumulator and that's way input pressure of the hydraulic motor is higher than it was in the first cycle. The possibility of usage of the secondary power source is controlled by on/off valve (7) (Fig. 1). The main directional control valve, controlled by the PI controller, reduces the volumetric

flow rate in the drain line of hydraulic motor to avoid exceeding acceleration limits of the vehicle.

Fig. 3 presents a comparison of the power of combustion engine in conventional drive system N_s and drive with energy recovery system N_{acc}. To estimate energy requirement in the compared systems always was chosen the same simulation time interval, i.e., the second cycle. The difference in areas under the graphs of power illustrates energy recovery in percentage.
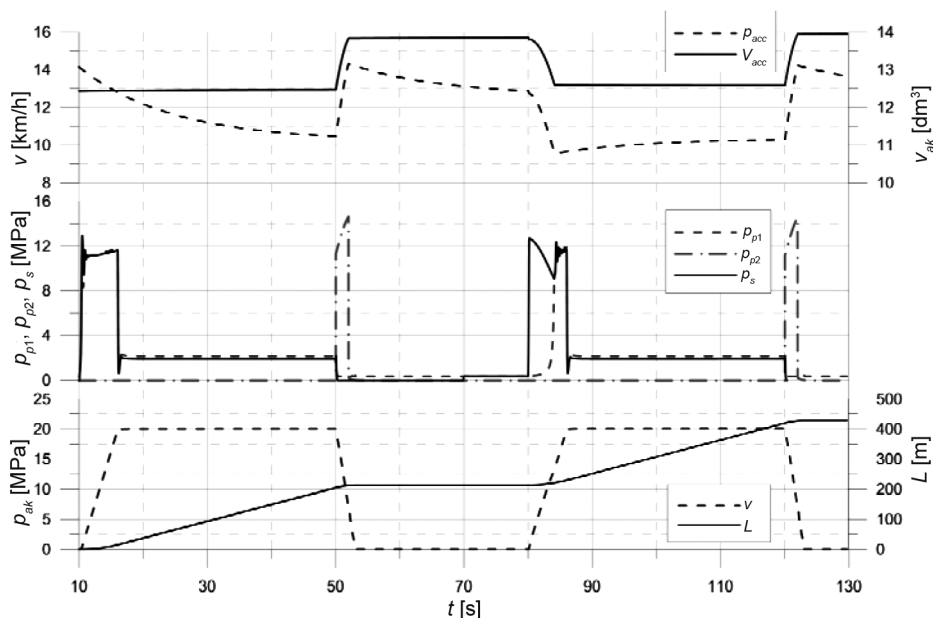

Fig. 2. Exemplary of hydrostatic transmission working parameters with energy recuperation, for 1500 kg vehicle weight riding with velocity 20 km/h

In Fig. 4 the energy yield of the drive system, depending on the set speed of the vehicle for one exemplary configuration of components that store the kinetic energy during the braking phase. The efficiency of the proposed system is decreasing with increasing of vehicle speed. It is the result of increasing the input pressure of the hydraulic motor in the acceleration phase, which significantly limits the possibility of using the stored energy at a lower pressure in the hydro-pneumatic accumulator. Assumptions of the operating cycle are unchangeable, so the vehicle accelerates to the set speed at the same time i.e. 5 s.

Vehicle drive system with a total weight 1000 kg, speed 15 km/h, has a distinctly low value of energy recuperation. It comes from the relatively low inertia of the vehicle and the need to supplement the flow rate by the main pump to keep the required delay resulting from the assumed cycle with simultaneous loading hydro-pneumatic accumulator.

The selection of elements of energy recovery system has a significant impact on the value of the expected energy savings. Required parameters of these components depend strongly on the assumed cycle of load and traction settings. Fig. 5 is a 3D graph, which shows that
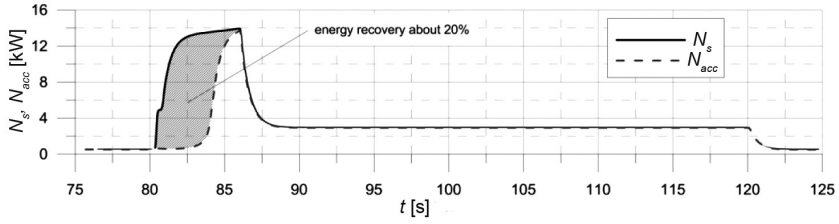
Fig. 3. Comparisons of the power of combustion engine in classic system and in system with energy recover for a vehicle with a total weight 1500 kg and a speed 20 km/h
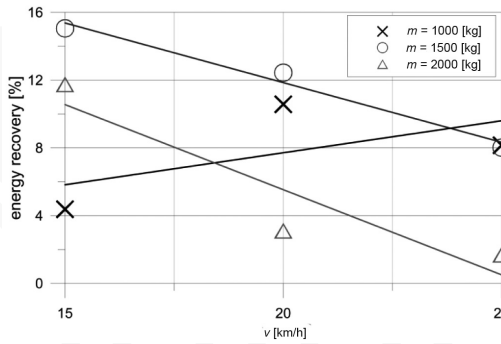

Fig. 4. Values of energy recovery as a function of vehicle speed for different masses of the total for the nominal volume of the hydro-pneumatic accumulator equal 20 dm^3 and displacement of auxiliary pump equal 40 cm^3/rev
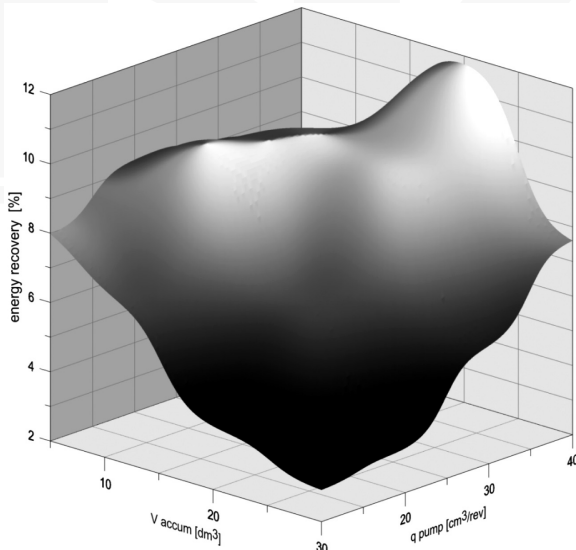

Fig. 5. Energy recuperation as a function of hydro-pneumatic accumulator size and pump displacement for vehicle total mass 1500 kg driving with velocity 25 km/h

for the vehicle with total weight 1500 kg and phase of constant travelling speed of 25 km/h, the most beneficial system of energy recovery from the point of view of efficiency requires pump of displacement volume 40 cm^3/rev and hydro-pneumatic accumulator with a nominal volume of 20 dm^3. Presentation in a similar way other parameters of the proposed system allows to select the best possible configuration.

4. Summary

During simulation was reached more than 10% energy saving in the test cycle. It confirms the validity of the assumptions of designed structure of the proposed energy recovery system. The percentage energy saving is strongly dependent on the working cycle of the vehicle. Long periods of standing and running with constant speed reduce the efficiency of the energy recovery system with hydro-pneumatic accumulator. The energy losses are result of thermal transmittance of accumulator shell. In vehicles with combustion engines these losses can be reduced by directing hot gases from the exhaust system on the accumulator shell.

Another way to use the proposed energy recuperation system is to work the system in the strategy of temporary increase the power of hydrostatic transmission. The oil pressure in the hydro-pneumatic accumulator can be set above the opening pressure of the relief valve in the main hydraulic system. It allows for a temporary increase of acceleration of the vehicle in the initial phase or helps during star motion of overloaded vehicle.

Weight of additional elements depending on the configuration and will not significantly influenced on complete vehicle kerb weight (max. to 5%). The cost of energy recovery system should be about 1 000 Euro. It represents about 10% of price increase of a new vehicle.

Analysis of simulation results indicate that one of the ways to maximize energy savings in the drive system of the vehicle is the selection of components of subsystem energy recuperation to the most common working cycle. Further work will give attention to improving control strategy, so that system could be more universal. Also road tests will be carried out on the modified transport vehicle, where the electric drive system was replaced by a hydrostatic transmission.

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