DESIGN OF AN ENERGY RECOVERY SYSTEM FOR PUBLIC TRANSPORT VEHICLE
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ABSTRACT
This paper describes some principles of kinetic energy recovery. Due to their key properties one of them is applied on a
design of a kinetic energy recovery system for a public transport vehicle. Basic calculations are conducted with respect
to the vehicle life cycle. Furthermore a mathematical model of the system is created using MATLAB/Simulink in order
to design and optimize components of the system. To conclude this paper, some thoughts on enhancing regenerative
braking process efficiency are mentioned.

KEYWORDS
Energy recovery, KERS, MATLAB/Simulink, mathematical model, public transport, driving cycle.

INTRODUCTION
Despite the fact that transit tends to be more effective than ever, it is still overlooked that the most significant losses are
caused by deceleration. During braking process the kinetic energy of the vehicle is transformed to heat energy which is
impossible to re-use. The key idea of energy recovery systems is to transform the kinetic energy to a different kind of
energy which might be used again for propelling.

GENERAL OVERVIEW
Parameters for comparison
Energy density $[J \cdot kg^{-1}]$ is equal to the capacity of the storage system divided by overall mass of the system.
Power density $[W \cdot kg^{-1}]$ is equal to power that can be delivered divided by overall mass of the system

Mechanical energy recovery systems
This type of system is based on flywheel technology. Rotating flywheel stores kinetic energy. CVT transmission is used
to generate force (driving or braking). This approach is known for decent efficiency, great power density and low
energy density. It is not very suitable for transferring large forces due to the CVT transmission. Similar system was
developed for Formula1 known as KERS and it weights around 30 kg.

Electric energy recovery systems
This system utilizes batteries or ultracapacitors as energy storage. Electric motor/generator is used for generating force.
This solution is characteristic for good energy density and low power density. It can be found it Formula 1 as well and
is the only mass-produced energy recovery system although it is not very efficient.

Hydraulic energy recovery systems
Hydraulic-based system utilizes hydraulic accumulators for storing energy and hydraulic pump/motor in order to
generate force. These systems have great power density but low energy density. Furthermore they are able to generate
large forces and are suited for heavier applications. They are also the cheapest to manufacture of these three approaches.

DESIGN OF AN ENERGY RECOVERY SYSTEM
During the design process such system was developed for public transport bus. Due to a need of large driving forces and
frequent rate of deceleration, hydraulic-based approach was selected. Irisbus Citelis 12m was chosen as a reference
vehicle because of the fact that can be seen in Pilsen.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>11 990</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>2 500</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>3040</td>
</tr>
<tr>
<td>Overall weight [kg]</td>
<td>18 000</td>
</tr>
</tbody>
</table>

Tab. 1 - Parameters of Irisbus Citelis 12m
SYSTEM ARCHITECTURE

![Fig. 1: System architecture](image)

Parallel hydraulic hybrid system that was designed is shown in fig. 1. The main components are: high-pressure accumulator, low-pressure reservoir, pressure reducing valve, 4-way directional valve, variable displacement axial piston pump, electromagnetic clutch, secondary gearbox and electronic control unit.

During ride at constant speed the electromagnetic clutch is decoupled. When driver presses the brake pedal the directional valve switches to the left position, the clutch engages making the variable pump transport hydraulic fluid from the low-pressure reservoir to the high-pressure accumulator. This process leads to pressure increase in the accumulator and therefore braking torque is generated according to eq. 1,

$$ T = \frac{\Delta p \cdot V_g}{20 \cdot \pi \cdot \eta_{sh}} [Nm] $$

where $\Delta p$ represents pressure different between high-pressure line and low-pressure line and $V_g$ is equal to the volume that is transferred per one revolution of the pump. In case of acceleration, the valve is switched to the opposite side which causes alteration of flow direction out of the high-pressure accumulator. The torque is still given by eq. 1 but has a different direction and leads to increase in vehicle velocity.

**Concept of the secondary gearbox**

The most important parameter for the design of the gearbox is a load. To create a load spectrum ECE driving cycle (fig. 2) was used. This driving cycle is used to describe traffic behavior in large cities and it accurately describes driving conditions of a public transport bus too.

![Fig. 2 – ECE driving cycle](image)

By taking derivative of ECE driving cycle function with respect to time, a function of acceleration $a(t)$ is gained. By multiplying values of acceleration by mass of the vehicle, function of force $F(t)$ is obtained. Driving resistances are taken into account within calculation as well.
Multiplication of force values by tire radius results in torque at rear axle. By dividing values of torque by final drive ratio torque at the input of the secondary gearbox is obtained. Consequently, creating of the load spectrum itself is not complicated. With regards to this approach bevel gears and bearings are designed to last 500 000 kilometers. Gear ratio was set in such way so that the operational speed of the system ranges from 5 to 55 km/h.

Mathematical model of hydraulic hybrid system
In order to design other features of the system it is necessary to create a mathematical model of the system. To do so MATLAB/Simulink was used. Hydraulic system is described by a set of differential equations which is solved numerically. The aim of the simulation is to:

- Optimize accumulator capacity
- Choose suitable pump in terms of size and power
- Choose suitable size of the directional valve
- Obtain performance data of the system
The mathematical model is shown in fig. 5.

There are two initial conditions for the solution. First of them being high-pressure accumulator at 0 % capacity and the second condition is related to initial velocity of the vehicle which was set to 30 km/h. Other parameters of the model, especially the capacity of high-pressure accumulator, varied in each simulation and the goal was to optimize those parameters so that during deceleration process the pressure in high-pressure accumulator reaches 35 MPa at the same moment when velocity decreases to 5 km/h which is the minimal operating velocity given by the hydraulic pump. Results of the deceleration simulation can be found in fig. 6 and fig. 7.
According to the simulation results in fig. 6 it seems that the braking time is too long to be utilized solely by the energy recovery system. This is partly caused by the nature of the initial condition. Pressure difference between the HP line and the LP line is quite low during the first 15 seconds. Therefore braking torque generated by the pump is also low with respect to eq. 1. As the pressure difference builds up braking becomes more effective although conventional brakes still have to be preserved.

Figures 8 and 9 prove that 18-ton vehicle can be accelerated from 5 to 15 km/h just by the energy gathered during deceleration from 30 km/h. It is also shown that acceleration is not very quick as long as pressure difference drops beneath 6 – 8 MPa.

**Summary of results obtained by the mathematical model**

Using MATLAB/Simulink led to selection of suitable hydraulic pump. Bosch Rexroth A4VG 280cc pump was chosen as a convenient solution. The capacity of the accumulators was determined to be 125 liters. Appropriate directional valve was selected with respect to the peak value of flow, which is 600 liters per minute and this also helped with calculating pipeline diameter which was set to 40 mm. Performance data of the system shows that it is possible to decelerate from 30 km/h to 5km/h and accelerate again to 15 km/h solely by hydraulic energy recovery system.
ENHANCING ENERGY RECOVERY PROCESS
Mathematical model proved that regenerative braking process is not very effective at low pressure differences between HP line and LP line. In order to improve overall efficiency the high-pressure accumulator should always be pressurized and never become empty of fluid. Another way to improve energy recovery process is by cooling the high-pressure accumulator during deceleration. Within the mathematical model adiabatic process is considered. However, isothermal compression is less demanding in terms of required energy. Cooling the accumulator during deceleration would lead to reaching the peak pressure earlier, which might allow using larger accumulators to slow the vehicle down to same velocity. Larger accumulator at the same peak pressure provides more energy for acceleration. Figure 10 presents the hydraulic energy recovery system that was developed during the design process.

![Hydraulic energy recovery system](image)

**Fig. 10 - Hydraulic energy recovery system**

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REFERENCES


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