POTENTIAL ENERGY REGENERATION IN HYDRAULIC SYSTEM

Jari Holopainen, Matti Juhala

Aalto University, Finland

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Aalto University is a newly created university at beginning of 2010 from the merger of three Finnish universities: the Helsinki School of Economics, the University of Art and Design Helsinki and Helsinki University of Technology – all leading and renowned institutions in their respective fields and in their own right.

Introduction

Today fuel consumption and energy efficiency plays important role in heavy duty vehicles. Also the performance of operation cycle, which means decreasing the amount of time used to a certain work task, has become more important parameter in system design. In many cases the work machines involve process cycles where energy is used for some operation, e.g. acceleration or lifting, and is released in counter-operation (breaking or lowering). To improve the energy efficiency of such a work machine, it is necessary to investigate the possibility of using regenerative methods.
By regenerative methods we mean systems which restore the releasing potential or kinematic energy of the operation cycle when it is possible and uses the stored energy in next cycle. In regenerative systems the mechanical energy is stored either in electric or hydraulic form. The stored energy is lower than the next operation cycle needs because of frictions and losses of regenerative system. Therefore the regenerated energy can be used to only facilitate the work and some external energy source is needed. In hybrid machines this is solved by using electric motor to help combustion engine in acceleration or the combustion engine starts when recharging the storage is needed.

The power transfer of heavy duty vehicles is usually implemented using hydraulics. In such machines breaking or lowering functions are controlled by transforming the kinetic or potential energy to heat energy using valves and orifices. The regenerative system for hydraulics could be implemented by installing a hydraulic motor parallel with the pump taking the energy for motor from a hydraulic accumulator. This of course adds complexity and cost of the system and also adds moment of inertia and friction to the axle of the pump-motor system. Another option could be to converter the energy to electricity and store it in capacitors and to use it while operating the pump. This adds energy losses, because of the growing amount of energy form conversion needed.

While studying regenerative systems a new idea was generated for accumulator application. The accumulator is still installed parallel for the pump. However, the main idea is to use hydraulic accumulator as a feed pump. Accumulator will be connected to pumps intake line and it reduces the pressure difference over the pump, so respectively it reduces the needed torque from the prime motor. It’s an advantage that the accumulator is relatively small, but still can do the job with good effort.

The aim of this study is to present a novel hydraulically implemented regenerative system. The results of this study consist of simulations and experimental measurements.

The novel regenerative system was firstly investigated by a simulation model. System parameters were also optimized by simulation. Real test system was built to ensure the functionality and to validate simulation result.

Simulation model

The simulation model was implemented using Matlab Simulink software and SimHydraulics component library. Used components were mainly ideal, or they had constant efficiency not dependent of the pressure, flow rate or temperature. For example the model of the hydraulic accumulator is implemented without energy losses (heat transfer). However, the magnitudes of energy losses in accumulator are expected to be so small that they can be considered negligible because of short storage time.

In order to maintain the possibility to implement the developed regeneration into an existing system the main dimensioning of the hydraulic components were maintained. Therefore the only variable in this case was the accumulator. The changeable parameters are the size and the pre charge pressure. In order to find an optimal solution their selection was based on simulation model where they can be easily varied.

Experimental test-rig

To validate the simulation results, an experimental test setup was build. With that the characteristic and functionality could be investigated. Due to some economical reasons, a smaller accumulator, as compared to the simulation results, was forced to be chosen, but in the other hand, it is a distinct situation, and we cannot always select the optimum components. A 4 l accumulator was used and the optimization for the pre charge pressure was made with the same simulation model using parameters of the selected accumulator. Result indicated to use 125 bars as pre charge pressure. The whole pressure zone was afterwards tested with the real test system.

The circuit can be seen in figure 1. Although in the figure 1 is shown a 2/2 poppet valves, instead were an old 4/3-proportional valves used in the first experimental setup. They have a notable amount of leakage and therefore the results are not as good as they could be.

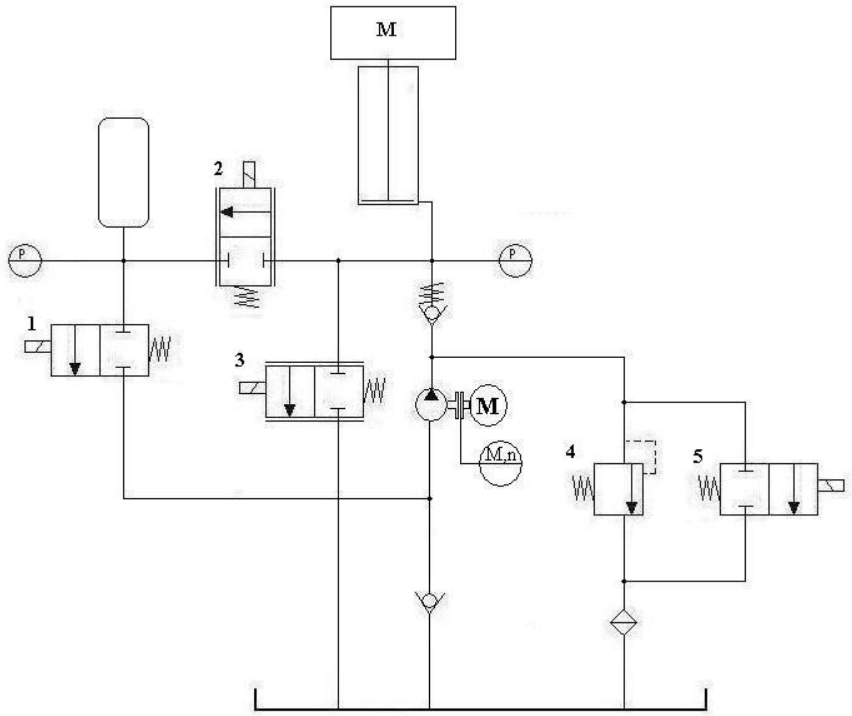

Figure 1: The schematic drawing of hydraulic circuit

Components

One of the main requirements for the system was that the pump could handle high inlet pressure. Therefore an axial piston motor was selected to replace the pump.

Component	Description
Pump	Parker F12 19cc/rev
Accumulator	4 L, bladder, nitrogen filled
Cylinder	63/32/200

System

The functionality of the system is simple. When there is no work needed, either the electric motor is shut down, or the idle valve (5) is activated. When we want to lift the cylinder, the idle valve (5) is shut and the flow goes straight to the cylinder, and the motion is stopped again by opening the idle valve (5). When the cylinder needs to be lowered, the charge valve (2) is opened, so the load and mass of the cylinder and mechanism charges the accumulator. If the velocity of the cylinder is too slow, the by-pass valve (3) can be opened to let some of the oil to return to the reservoir. If the accumulator is charged, the feed valve (1) is opened during the next lift operation. So the pressure of the accumulator is connected to the inlet of the pump reducing the pressure difference over the pump. When the accumulator is empty, the feed valve (1) is shut and the rest of the lift is done normally. Pressure relief valve (4) is added only to prevent the pressure raise when the cylinder is driven to the end.

The pumps input power was measured from the shaft of the pump. The torque of the shaft was measured with torque sensor and the rotating speed was controlled with frequency converter. Pressures of the system were also measured, so the accumulator operation could be observed. The test cycle program used information about the position of the cylinder to change modes between lift and lowering.

Testing cycle

The test cycle began with empty accumulator and the cylinder in zero position. First the loading mass was lifted to upper position using pump without assistance. When the cylinder reached its upmost position the valves 2 and 5 were opened for the lowering phase. With valve 2 the lowering speed and charging process could be controlled and with valve 5 the pump was set to idle operation. While the mass comes down, the accumulator is been charges. During the lowering phase the speed is measured and can be controlled by opening valve 3 in the case when the speed of cylinder was reducing below set value. When the cylinder comes to its lowest position, a second lift can be started. Valves 2, 3 and 5 are closed and valve 1 is opened. Then the flow from accumulator is directed to the inlet of the pump, reducing the pressure difference over the pump, and so reducing the needed torque from the motor drive. When the accumulator was run down, rest of the fluid was soaked from the tank. These two adjacent lifting operations were compared in order to estimate the energy saving possibility.

The valve openings were controlled and the measurements were made with LabView software.

Results

Simulation results

Optimization of parameters was investigated between 2 and 10 litres of volume of the accumulator and 100 to 160 bar of pre charge pressure. The minimum level of volume was limited to the size of used cylinder and upper limit was a well appraised maximum size. Of course it would be best to use as large accumulator as possible, but in mobile machines, which are our main interest area, the available space is highly limited. Upper limit of pressure range was defined by the load of the cylinder, so that the mass is still capable to charge the accumulator. Lower limit is again a well appraised pressure value, so that the recovered energy is relatively high. The simulations indicated that the best combination would be 9 litres and 135 bars of pre charge pressure. Then the energy conservation ratio was 89%. Absolute value itself is not reliable because of the simplified model. But we can assume, that the parameters aren’t prone for the phenomenons, which were not taken in to account on the model.

However, usually the optimal components cannot be chosen for unrelated reasons for example lack of space, or the component on that size is not available. The test rig had to be built with 4 l accumulator, therefore there was a new optimization made for the 4 l accumulators pre charge pressure. The results are shown in figure 2.

From these results can be seen that the optimal pre charge pressure would be 125 bars. In the simulation model was a parameter for the lowering time, and as the pre charge pressure gets higher, the lowering time increases.

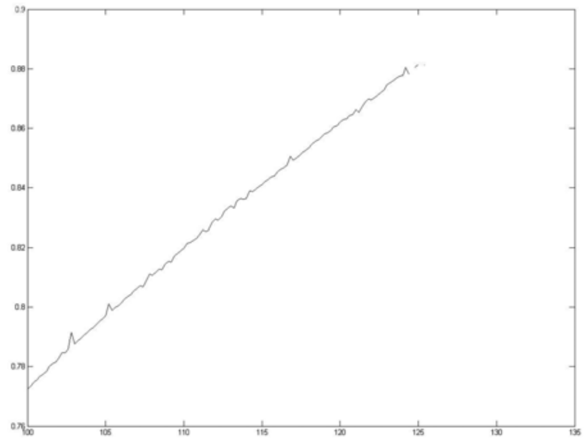

Figure 2: Pre Charege pressure optimization for the 4 l accumulator

Experimental results

The leakage of the valves was investigated by driving the cylinder to its upmost position and closing the valves and measuring how fast the cylinder creeps down. The results are shown in figure 3

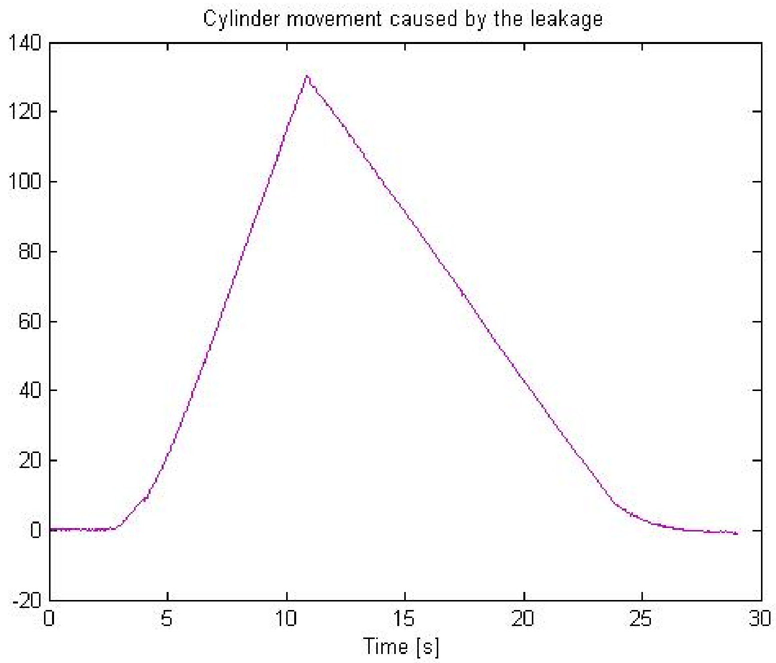

Figure 3: Cylinder movement caused by the leakage

Movement starts at time t = 10s and ends at t = 23.5. In this time the cylinder has moved 120mm. The speed of the cylinder is therefore 9.5 mm/s. Then we can calculate the flow through the valves with following equation.

$$Q = v \cdot A = v \cdot \pi \cdot r^2 = 1{,}78\ l/\min \qquad (1)$$

The leakage is notable. That's why the cycle was done without holding time. Also the type of valve is not optimal for this application because the spool valves are not leak free and they are not good valves for accumulators, but still the results were relatively good. It is unlikely that in real system, the holding time would be close to zero, but by using either poppet valves or digital flow control units, the leakage is clearly smaller problem. The results from the actual system are shown in the following table 1.

Table 1: Energy conservation in per cent

	120bar	135bar	140bar
300 rpm	53,77	48,98	54,21
500 rpm	44,58	38,54	40,82

The results might look illogical at first; because the lowest and highest pre charge pressures gives better results than the middle pressure level. This can be explained as the accumulator is charged to higher pressure; the pressure difference is lower over the pump, so the effort of the feeding phase is higher. And on the other hand, lower pre charge pressure loads the accumulator more full, so there is more fluid an therefore the time of the feeding phase is longer. It seems that the combination of these two phenomenons isn't working so efficiently. Of course the size of the accumulator is important. As the optimization showed, the best effort is gained with 9 l accumulator. In larger accumulator the pressure change is slower when the accumulator is filled, so the given power is more constant.
Also the higher rotation speed of the pump reduces the effort. This can be explained by the pressure loss of valve 1, when the flow is clearly higher over the valve.

In Figure 4 the position of the cylinder and power from pumps shaft are presented.

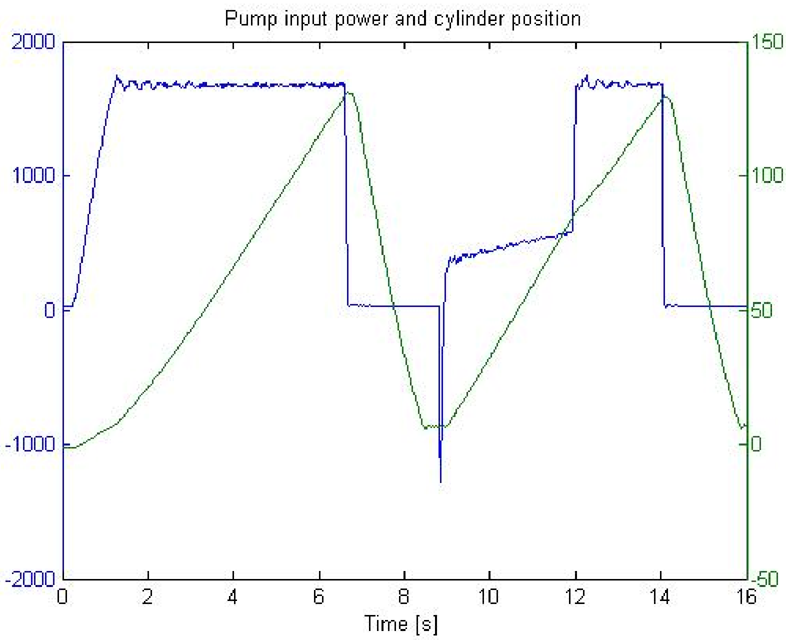

Figure 4: Pumps input power [W] (blue, left hand side) and cylinder position [mm] (green, right hand side)

Discussion

In the first experimental tests, the measured energy conservations varied between 40% and 55 %. There are two main reasons why the results were much lower than what was seen during the simulation phase. First of all, the idealization of the simulation model was affective, for example a heat transfer of the accumulator was not taken in to account. Other reason was the used valves. Instead of 2/2 cartridge valves, old traditional 4/3 spool valves were used. They even appeared to be somehow worn out, so the leakage was notable even as compared to new spool valves. Off course the leakage is still an issue, although the valves would have been new. Even these valves gave positive results for energy conservation in hydraulic systems involving lifting and lowering showing that the basic idea is functioning.

The idealization of the hold time was, of course, a prevention of the leakage problem, but it can also be a real situation. In an advanced system there can be various actuators from which at least one is used all the time. For example an excavator, where an experienced operator uses multiple actuators at the same time and at least some of them at all times. So with more intelligent controlling system, the regenerated flow could be driven straightly to other actuator or momentarily to the accumulator. Also there could be used a combination of more than one accumulator with various pressure levels. This possibility is also under our investigation now.

The leakage is not the only problem when the energy storage time is long. Even though, if the valves were leak free, the pressure in the accumulator reduces a little bit over time, because of the thermal loss. There are possible solutions for that which we are surveying further.

The new test system is under producing. The proportional valves are substituted by Digital Flow Control Units (DFCU) whose leakage is minimal and the cost is lower. And they are commercially available.

The usage of regenerating systems in every kind of machines and devices are certainly becoming general. There are numerous of projects around the world investigating the regeneration and energy conservation.

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