PRB - Regeneration of potential energy while boom-down

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Abstract

This paper introduces the results of a concept study of a hydraulic system called Power Regeneration Boom (PRB). Therein the potential energy of an excavator boom is either regenerated directly or stored in an accumulator and fed back afterwards. Additional costs are kept small by using already existing components for energy recovery. Fuel savings of about 3 l/h and more are feasible and validated by vehicle tests.

KEYWORDS: regeneration, recuperation, hybrid, energy efficiency, fuel saving, construction machinery, excavator, boom, accumulator

1. Introduction

Today higher productivity in combination with less energy consumption is required by the mobile equipment market. At the same time only slight cost increases of the overall equipment are accepted. Influenced by this market trend one important design goal for Rexroth is to provide mobile control components with energy regeneration and recuperation features that improve the energy efficiency of the machine significantly.

This paper introduces a new approach of a modular Power Regeneration Boom System (PRB) that addresses both demands. The basic idea is either to regenerate the potential energy of a boom directly as hydraulic energy instead of dissipating it or to temporarily store the energy in an accumulator. During the next working cycle, the stored energy is fed back into the implement hydraulic system, thereby relieving the combustion engine. In order to keep additional costs small already existing pumps are used to distribute the gained energy from the suction line of the pump into the system.

Finally the feasibility and the fuel saving potential of the system are proven by vehicle tests. Above all the hydraulic hybrid concept reveals its full energy saving potential in large excavators. The more intensive the boom down and up working cycles are, the greater the reduction in fuel consumption through PRB is.

Rexroth is currently carrying out a PRB concept study for the various control concepts in mobile equipment and is considering to start a development project in the first half of 2012.

2. Energy balance of implement hydraulics

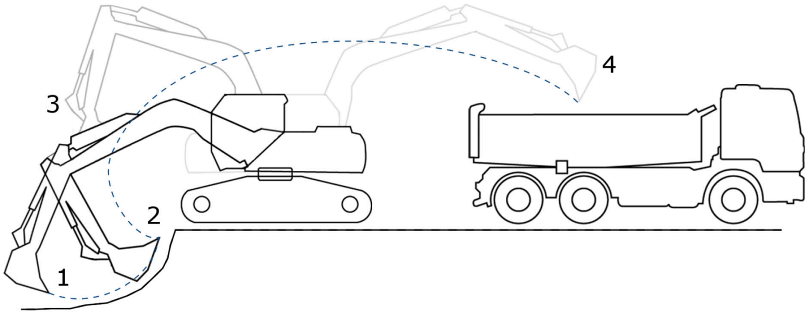


Figure 1: Excavator during digging and loading

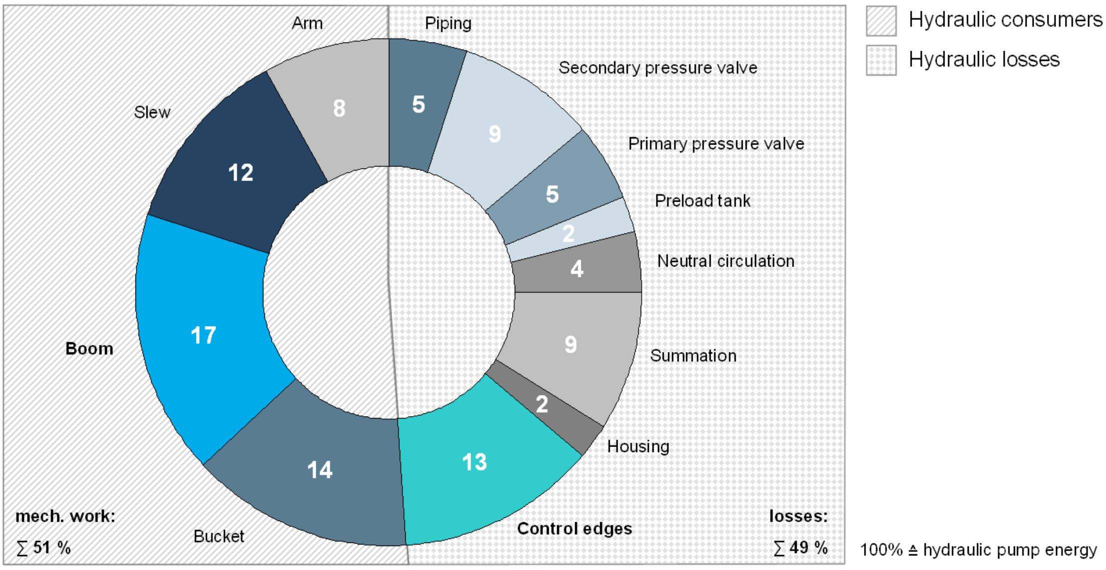


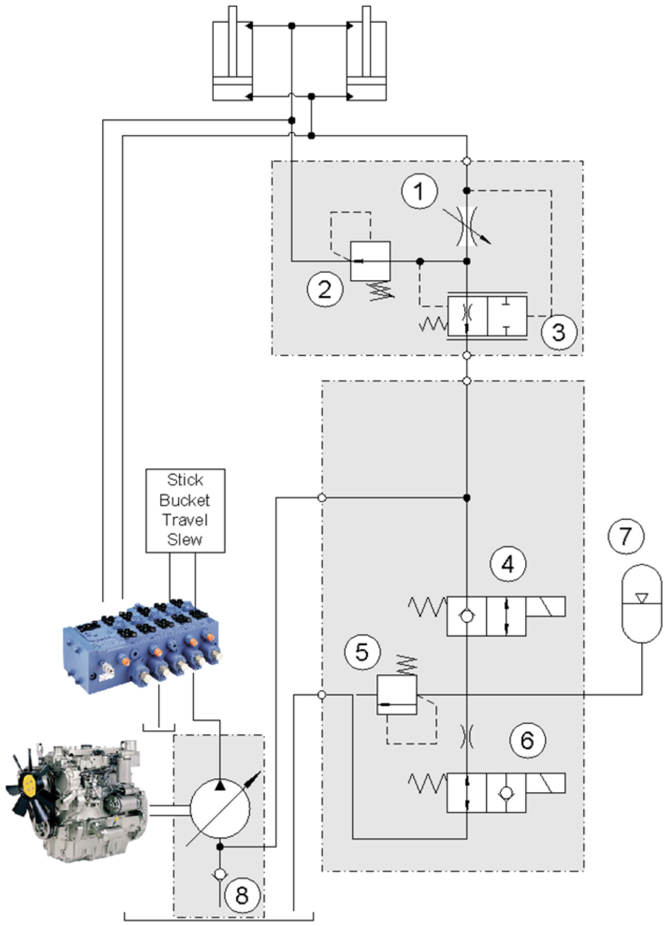
Figure 2: Distribution of hydraulic pump energy during digging and loading duty cycle

In order to identify the most relevant energy consumers and losses the typical energy distribution in an excavator is analyzed by measurements. The distribution itself strongly depends on the duty cycle. As an example, the machine needs much more energy for digging and loading than for grading some ground. To achieve comparable results, it is important to define a representative working cycle to evaluate the energy consumption. Despite the fact that an excavator is used in a lot of different ways, digging in combination with loading of a truck is one of the most common duty cycles (**Figure 1**). Typical for this cycle is the high power demand for digging of the bucket into the soil and the subsequent rising and swiveling of the implement over the truck. After unloading the bucket, the excavator swivels back to the initial digging position and lowers the implement with maximum speed.

The energy distribution during this working cycle has been measured on a machine in a realistic environment. The results are shown in **Figure 2**: Only 51% of the total hydraulic energy of the pumps are transferred into mechanical work by the hydraulic actuators; 49% of the overall hydraulic energy are losses. With a portion of 17% the two boom cylinders do the most mechanical work of the entire system. Apart from the losses at summation- and pressure-valves (9% each), the energy losses at the control edges of the main valve-spools are the most significant ones (13%). These mainly occur on the valve's meter-out control edge while lowering the boom cylinders. In this operating condition a high flow rate has to be throttled from load- to tank-pressure. Therefore, technical solutions, which reduce these pressure losses by regeneration of the meter-out flow, are very beneficial for the overall energy efficiency of the hydraulic system.

3. Technical concept for regeneration

To regenerate the potential energy while lowering the implement, there are two different approaches. One is to directly transfer the energy back into the hydraulic system, the other one is to temporally store the energy in an accumulator and to feed it back into the system at a subsequent instant of time. In the application and duty cycle under consideration, almost no other consumer is operated while lowering the boom, except for the slew drive which might operate at low pressure levels. Thus nearly no energy is required for the other actuators during this time. Therefore with a direct regeneration, the energy can only be used for the cylinders of the boom itself, which can be realized by a regeneration line from the bottom to the rod side of the cylinders. Due to the area ratio of the cylinders however a certain portion of the meter-out flow has to be transferred into the tank at a high pressure level. Further, the pressure level on the rod side is so low, that even the regenerated meter-out flow has to be throttled a lot. Due to these facts, it is favorable to store either the energy in an accumulator for later use or to find other ways to regenerate the energy directly without huge throttling losses.



PRB Valve module

(1) Meter-out control edge

(2) Anti-cavitation valve

(3) Pressure compensator

Accumulator safety block

(4) Cut-off valve

(5) Pressure valve

(6) Unloading valve

(7) Accumulator

(8) Pump with high pressure suction line

Figure 3: Schematic hydraulic circuit of Power Regenerative Boom PRB

Focused on a solution with a minimum number of additional and modified components, Rexroth developed the valve-module Power Regenerative Boom PRB, which allows regeneration, storage and feed back of the potential energy of the implement **(Figure 3)**. The new part of the module is a separate valve, which is connected in parallel to the main control block. While lowering the implement the valve (1) in the PRB module is adjusted proportionally to provide a connection from the bottom side of the boom cylinders to a hydraulic accumulator (7)**.** To regenerate as much energy as possible, the valve completely replaces the meter-out notch in the main control block. A pressure compensator (3) in the meter-out line keeps the pressure drop at the control edge constant. Hence, the speed of the boom-movement is independent from the charging level of the accumulator as well as from the load on the implement. The flow to the rod side of the boom cylinders is still provided by the main control block. Additionally, an anti-cavitation valve (2) in the PRB-Module ensures a sufficient filling of the rod side to prevent cavitation.

For safety reasons, the accumulator itself is connected to an accumulator safety-block, which consists of a pressure valve (5) as well as a solenoid on/off-valve (6). The latter is normally open and connects the accumulator to the tank to ensure discharging in case of a machine shut down. A further on/off valve (4) is used to on the one hand actively control the regeneration of the stored energy in the accumulator and on the other hand avoid a complete discharge in standard-operation mode. A complete discharge would cause the bladder of the accumulator to hit the inner assembly during each duty cycle, which reduces the life expectancy of the accumulator. The information about the accumulator’s charging level is detected with a pressure sensor (not shown).

As discussed above, to feed back the regenerated energy into the hydraulic system under minimum pressure losses is a big challenge, as the pressure level of the actuators can differ from the accumulator pressure quite much. To solve this discrepancy, the energy is not fed back to the actuators directly, but to the suction line of the pump to reduce its power demand. To achieve this, the suction line of the implement pump is separated with a check valve from the tank reservoir. If the suction pressure is higher than the output pressure the pump even runs as motor. If the accumulator is fully discharged it is cut off. Thereby the pressure in the suction line decreases to tank pressure and the pump is supplied via the check valve from the tank reservoir.

With this valve assembly patented by Rexroth, the potential energy of lifted loads can be regenerated without the need of an electro-hydraulic closed loop control and independent from the type of main control block installed. Furthermore, with the connection to the suction line of the pump, it is possible to feed back the energy for hydraulic actuators independent from their pressure levels. As an alternative concept to this regeneration via the implement pump, it is also possible to supply suction lines of other pumps, which are installed on the machine too. Examples for such pumps are the fan- or pilot oil flow pump. As already existing pumps are used, the number of additionally needed components is low, which is especially beneficial in applications with little installation space. Above all, PRB is not limited to cylinders but can also be used for rotatory actuators such as winches.

4. PRB on experimental vehicle

Figure 4: Wheeled excavator with Power Regenerative Boom

For functional demonstration and to analyze the reduction in fuel consumption during typical duty cycles under realistic conditions, the new valve module Power Regenerative Boom PRB has been tested on a 14 ton wheeled excavator (**Figure 4**). The hydraulic circuit is in accordance with Figure 3. It is realized with a Rexroth M7-22 LUDV main control valve with the PRB module connected in parallel. To regenerate the stored energy optimally, the accumulator (nominal size 35 liters) is preloaded on a mid-pressure level and is connected to the suction line of the implement pump. For the results discussed in the following the excavator has been operated in a 90° digging and

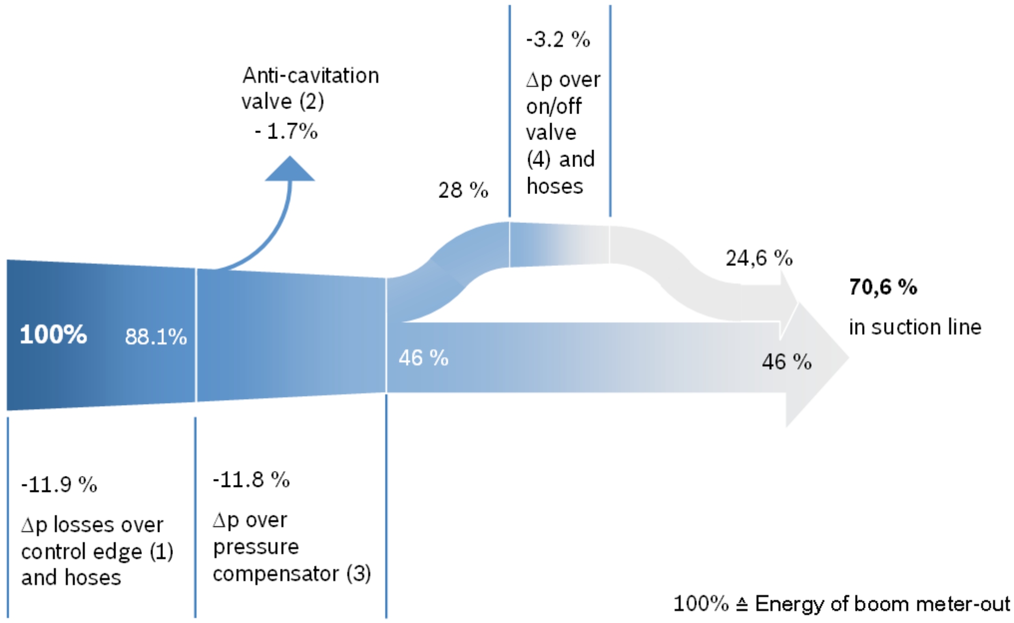


Figure 5: Energy distribution of boom-meter out flow during boom-down with Power Regenerative Boom

loading cycle. Within this cycle the implement is lowered at minimum weight as the bucket is unloaded before lowering the boom. In the light of desired energy savings, this can be considered as a worst case condition.

At first the energy flow during the boom-down movement is analyzed. Considering an energy amount of 100% at the bottom side of the boom cylinders before the movement, an energy flow chart in **Figure 5** shows the corresponding energy losses, which occur inside the PRB module while lowering the implement. Due to the pressure losses at the meter-out notch and the piping, approximately 12% of the energy gets lost. As the pressure levels in the accumulator and in the cylinders differ, further 12% of losses occur at the pressure compensator during throttling. While lowering the boom, the pump has to fill the rod-side of the cylinders. This oil flow is directly fed back into the suction line of the pump, without additional throttling. The portion of regenerated energy on this direct flow path is about 46%. The oil flow, which is not required by the pump, is automatically used to fill the accumulator. There, further losses occur, so that 28% of the potential energy have been transferred into the accumulator after lowering. In the following duty cycle, the accumulator is discharged via the suction line of the pump, thereby 3% of energy losses occur at the on/off valve. In total the Power Regenerative Boom module enables to regenerate about 70% of the potential energy.

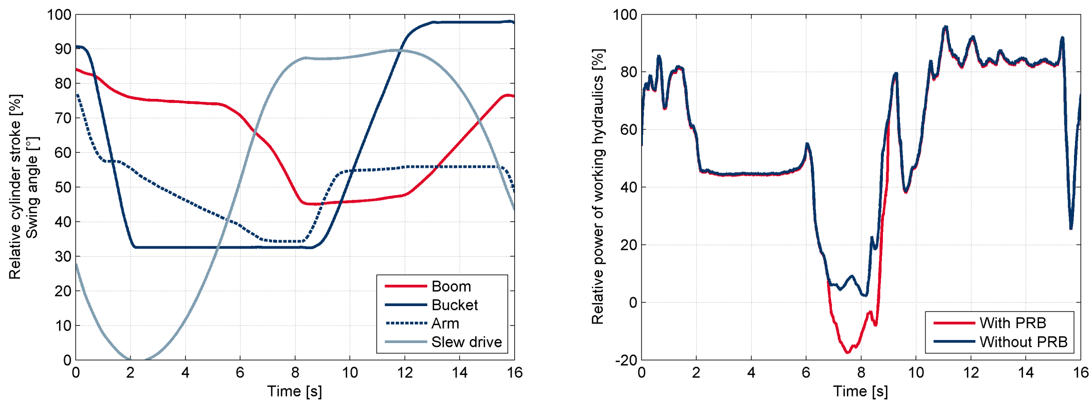


Figure 6: Measurement results for digging and loading duty cycle

In **Figure 6** measurements of the duty cycle described above are shown. On the left side the positions of the hydraulic actuators are depicted. In particular, the boom cylinders are lowered in the time period of 5s-8s at about 30%. The hydraulic power, which is needed to drive the implement, is shown in Figure 6 (right). Using Power Regenerative Boom, the power demand for lowering the boom has been clearly reduced. The pumps are partially even in motor mode and release their torque to the engine shaft. Hence the power demand for the drag torque of the combustion engine, as well as the demand of auxiliary consumers, such as the pilot oil pump or the fan drive, is decreased. For this reason the fuel consumption is reduced. Since the power demand of the auxiliary consumers is well above the power that is transferred to the motor shaft via PRB there is no danger for engine overspeed. In this case, as soon as the boom is at its minimum position the power demand equals the power demand without PRB, indicating that the accumulator is at a low level. This occurs since the excavator is still swiveling while the boom is lowered, which means that the oil flow is directly regenerated for the slew drive and not temporally stored in the accumulator.

To derive the amount of fuel saving from the reduction of hydraulic power through the use of PRB the engine characteristic has to be considered. Due to the low torque demand to the engine while lowering the boom, the engine is typically not at its optimal but rather at a disadvantageous operating point regarding fuel consumption. During the experiments in the above duty cycle with the 14 ton wheeled excavator equipped with PRB, the fuel consumption of the diesel engine has been reduced at about 0,9-1,3 l/h, by applying the Power Regenerative Boom valve module. As the amount of potential energy depends only on the duty cycle, the fuel saving also depends on the duty cycle but not on the type of main control valve installed. That’s why the fuel saving is given as an absolute value and not as a percentage.

As mentioned above, the potential of reducing the fuel consumption strongly depends on the machine itself and its duty cycle. Using detailed simulation models, fuel savings are predicted in early project phases already. Numerous models of different machine weights and machine types as well as different control systems were created and used during PRB development. Regarding PRB, the valve module has been analyzed in the 14 ton wheeled excavator as well as in a 45 ton material handler. In both cases the loads on the cylinders are extracted from measurements and are considered as external cylinder forces inside the model. With these modeled systems, one is able to analyze the energy consumption within the machine at defined duty cycles and machine movements.

Figure 7 outlines the basic relationship between the machine weight and the expectable reduction of fuel consumption predicted by the simulation model. As the static holding pressure in the cylinders as well as the meter-out flow rate rise with the machine weight, the potential for energy regeneration also increases.

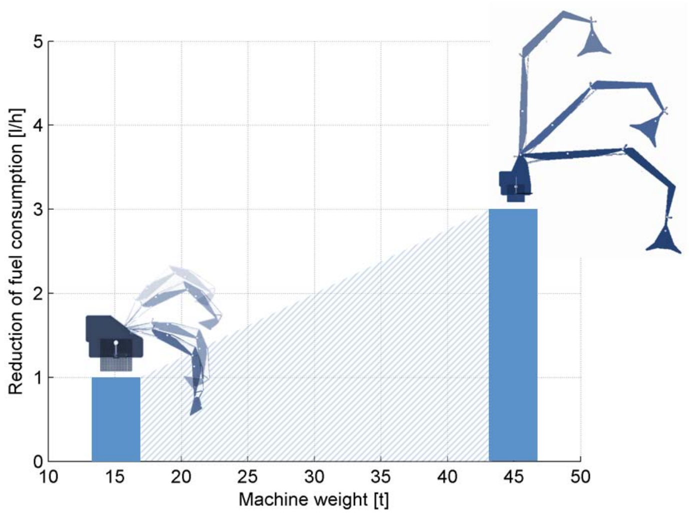


Figure 7: Influence of machine weight on reduction of fuel consumption

For the 14 ton wheeled excavator during the digging and loading duty cycle, a reduction of about 1 l/h is simulated and proven by experiments. A fuel saving of about 3 l/h was simulated for the 45 ton material handler.

5. Conclusion

Summing up, the new valve module Power Regenerative Boom (PRB) enables the regeneration, storage and feed back of the potential energy of the Boom through a hydraulic accumulator in all up- and down cycles of the implement. The concept has been tested on a 14 ton wheeled excavator under realistic working conditions in different duty cycles. A reduction in fuel consumption of 1 l/h is demonstrated. Further, the relation between the machine weight and the potential of energy saving is analyzed by means of simulation models. For example, in a typical duty cycle of a 45ton material handler the fuel consumption can be reduced by 3 l/h by use of PRB.

The presented PRB valve concept has a high capability to save energy along with a high modularity and compatibility to different hydraulic systems and main control valves. Currently, the concept is evaluated on different types of machines and their hydraulic systems. Based on the results of the evaluation Rexroth will consider to start a corresponding development project in 2012.