Application of Power Regenerative Boom system to excavator

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Abstract

This paper is presenting the application of Power Regenerative Boom(PRB) system to excavator. In order to increase the fuel efficiency of the excavator, potential energy of the front structure is recuperated by the hydraulic hybrid system with electric-hydraulic control, during boom down motion. Charged energy into accumulator is reused after boom down motion, the pressurized oil goes to hydraulic motor. The hydraulic motor is mounted on the engine PTO(Power Take-Off), therefore output torque of the hydraulic motor assists the diesel engine directy, it leads to decrease fuel consumption of diesel engine. After the system design and simulation investigation, the presented system was installed into Doosan's 38ton excavator, DX380LC-3 model, and the energy saving result was verified by a digging and dumping repetition test. The test result shows that fuel consumption was dramatically decreased by 5.0 L/hr compared to the standard DX380LC-3.

KEYWORDS: Hydraulic Hybrid, Energy Recuperation, Fuel Saving, Energy efficiency

1. Fuel Saving Technologies for Excavator

The theme of fuel saving is very consistent and valuable technology in the modern industry. Various fuel saving technologies were already appeared to market by major excavator companies. Doosan's VBO (Virtual Bleed-Off, **Figure 1**) technology was successfully developed together with Bosch Rexroth and is currently in the mass production status. The VBO technology is changing Doosan's conventional excavator into a more efficient machine by using an electric main pump and an advanced hydraulic control, showing over 10% less fuel consumption /1/. The Caterpillar 336EH model was launched in 2013, consists of IMV style control valve, an electric main pump and a swing hydraulic hybrid technology, about 25% less fuel consumption than the standard 336E model /2/. Komatsu had developed electric swing hybrid excavator, PC200-8 in 2008, with about 25% less fuel consumption than the standard model /3/. Moreover, other excavator companies such as Liebherr, Hitachi, Atlas are also continuously interested in developing fuel saving technologies. Doosan Infracore is now researching the more fuel-efficient hydraulic solutions in various ways. This paper will introduce one of Doosan’s new fuel saving challenges together with Bosch Rexroth.

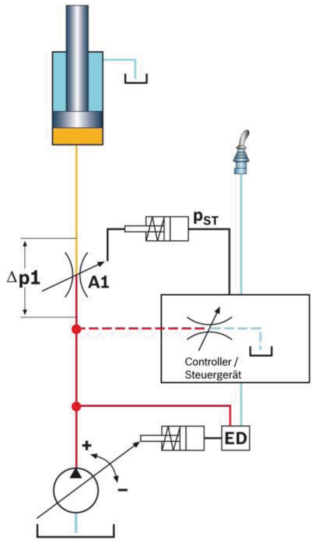

Figure 1: Doosan’s VBO (Virtual Bleed-Off) technology for fuel saving

2. PRB Concept Design

2.1. Introduction

Bosch Rexroth published the PRB Concept Study /4/ in 2012 with a hydraulic controlled PRB valve. Continuous development lead to the second generation of PRB, which increases customer benefits in terms of fuel saving rate and controllability by implementing an electro-hydraulic (EH) controlled system. The functional complexity was shifted into software. Due to that the valve block becomes slimmer, which affects costs as well as installation space. Furthermore, the EH strategy enables a state dependent control logic to bypass limiting compromises of a purely hydraulically controlled valve.

2.2. Requirement Engineering

Confirmed customer requirements in an early project phase leads to clear project goals. Stakeholder requirements have to be collected, clustered and confirmed. Beside performance issues like the excepted ratio of fuel saving or the required duration of boosting, installation topics, controllability and milestones the load cycles has to be appointed for the final proof of concept. All following concept refinements and functional development can refer to stakeholder requirements and will derive more detailed requirements for hardware and software.

2.3. Concept Study

The analysis and ranking of energy consumption in typical load cycle of the target application, investigations of power losses and unused potentials gives a first indication and leads the way to a proper hybrid solution. In a conventional excavator the potential energy of the boom is normally unused, which is the main idea of PRB to use this energy to save fuel. Hydraulic and mechanical losses observantly considered and regeneration flows subtracted, the boom down motion of the 38ton excavator DX380LC-3 from Doosan Infracore contains 16% potential energy in the given reference load cycle with respect to the overall energy demand of the engine. See **Figure 2**:

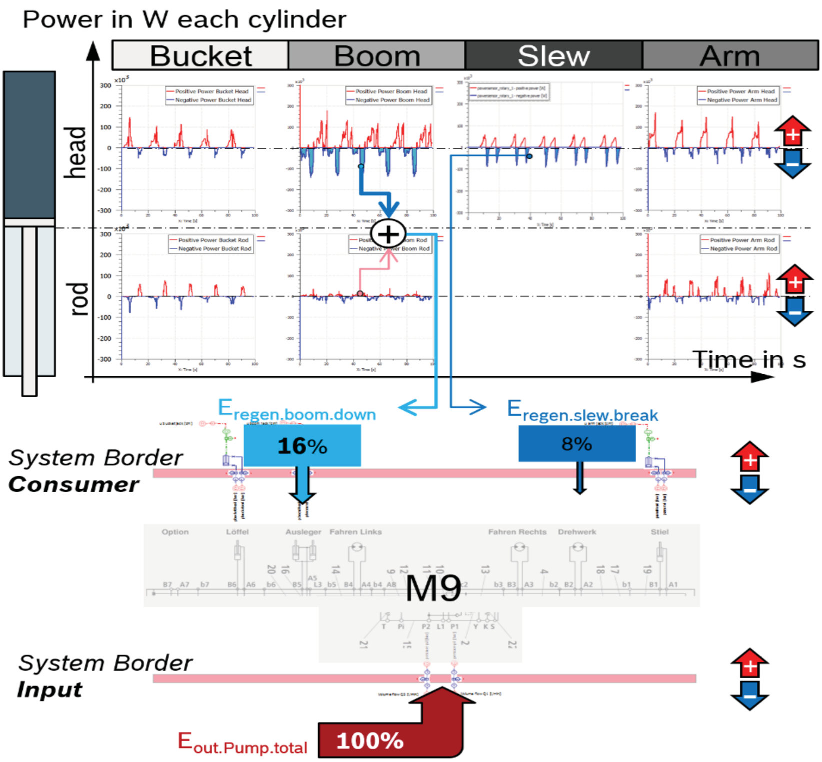

Figure 2: Energy Flow Analysis

Harvesting of boom energy means a system modification. Beside the objective to influence the original excavator layout as little as possible, the concept of PRB is an Add-On solution. The excavator series shall have the same modular layout whether standard or hybrid.

Following these restrictions in most cases a big challenge is to integrate an accumulator in a standard layout. The metering function of a standard main control valve is designed for a counter pressure of the boom head side during lowering near to reservoir level. Due to installing an accumulator the counter pressure will be much higher but the requirements in terms of controllability will stay the same. Therefore a component is necessary to enable a good controllability of the boom motion even with higher and variable counter pressure. The engine has to be involved into the hybrid system in a way that the released energy from accumulator and boom is used to reduce the fuel consumption during a load cycle. Finally a control device has to be considered.

2.4. System Design

Based on the development requirements, potential concepts of boom energy recuperation will be evaluated. The result of the assessment is the most promising solution in this early project phase.

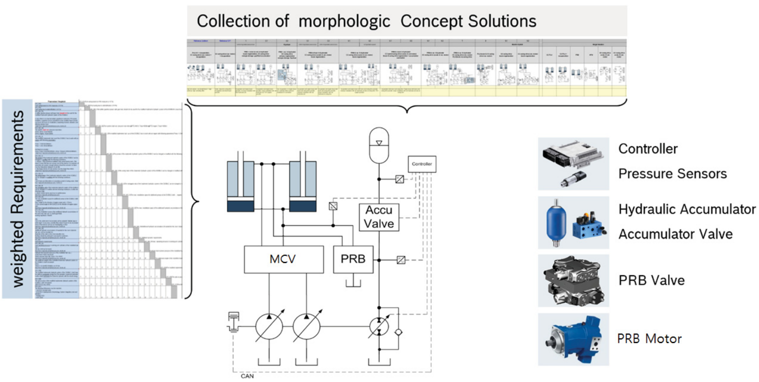

Figure 3: Conceptual System Design and Components

The conceptual System Design of the new PRB shows four main Components (**Figure 3**). The core component is the PRB valve block, which is connected in parallel to the existing main control valve and consists of two slices of the new control valve series from Bosch Rexroth control valve. Further components are a hydraulic accumulator including valve block for energy storage and a variable hydraulic motor, the Bosch Rexroth A6VM, to support the engine are included. A controller is processes the necessary information via pressure sensors at the head side of the boom cylinder, the accumulator and the high pressure port of the hydraulic motor. The required engine signal is detected via CAN. The final system design is shown in **Figure 4**.

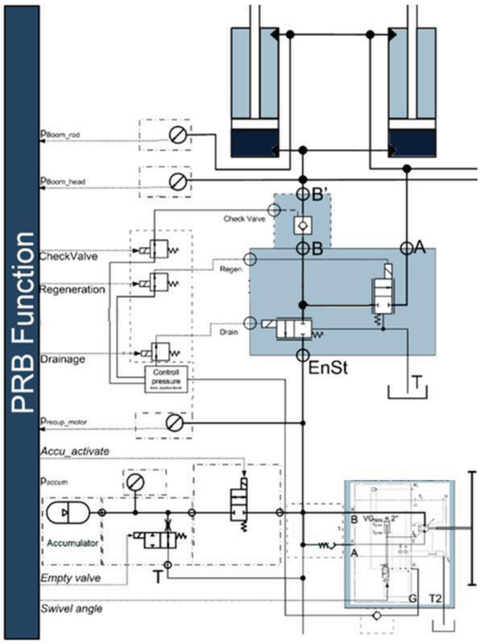

Figure 4: System Design PRB

3. Model Based Verification

During the design phase it is helpful to get feedback regarding system performance each development step. Model based system design and functional development including refinement of requirements is a feasible approach. Therefore a sufficiently detailed simulation model is required which is capable to simulate a realistic fuel rate since the major requirement of PRB is to save fuel during a load cycle. Simple energy flow analysis is a first indication but not meaningful in regards of fuel rate. A modification of the system which, even if only slightly, influences the timing between arm and boom speed will require an adaption of the operator behavior. Therefore, a simulation model was developed, the “virtual excavator”, specialized for system development to derive seamless results along the complete signal chain from operator signals and to the fuel rate, detailed hydraulic results as well as the trajectory of the working device including visualization. **Figure 5** gives an overview of all included components of the virtual excavator.

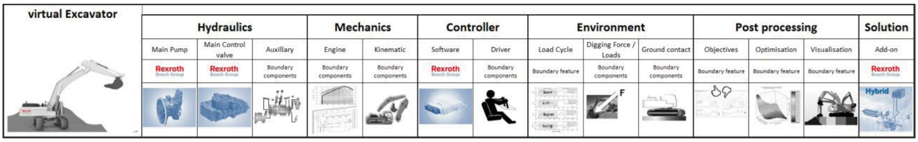

Figure 5: Overview of Components of the virtual Excavator

Hardware as well as software components of Doosan's DX380LC-3 are thoroughly validated parts of the virtual excavator. To completely model an excavator, boundary components like the engine, the excavator body containing the working device, hydraulic cylinders and the upper structure are included. The environment is modeled in terms of digging force and stated dependent on the bucket load as well as on the load cycle handling. The virtual operator /5/ to control the excavator realistic was developed in cooperation with the Stuttgart University. The model predictive operator showed the highest range of validity and the most reasonable control signals to maneuver the excavator through a 180 degree digging cycle, adapting properly to every system modification that was chosen to optimize the PRB solution. Simple linear PID based controller models showed a not acceptable behavior. The tool chain is shown in **Figure 6**:

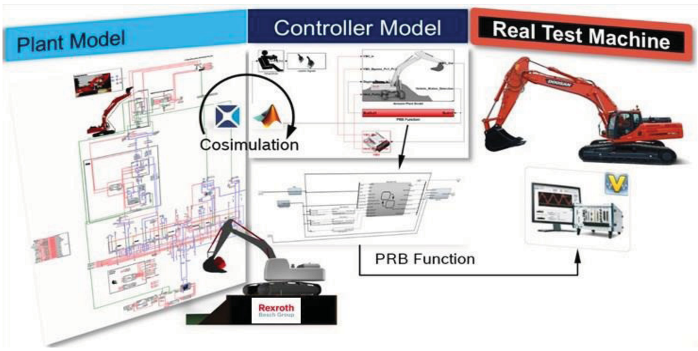

Figure 6: The virtual Excavator

A plant model inside AMESim and a controller model inside MATLAB interact via co-simulation. The controller model consists, beside all relevant excavator functions, of the PRB function. The identical model was also used as prototype software on the real machine. All PRB software functions were developed and optimized model based. In parallel, the actual test machine was prepared with the PRB. One pre-commissioning for basic installation tests and one commissioning for detailed parameter tuning were enough for the final proof of concept to validate the required fuel saving rate and controllability. Simultaneous engineering supported by model based development was one of keys for the successful development.

4. Performance Test with 38ton Excavator

In order to verify the actual effect of fuel saving, 38ton test excavator was built, implementing a PRB system based on the DX380LC-3, VBO system. The main hydraulic components used are listed as below (**Table 1**), also additional pressure sensors and solenoid valves.

Items	Specifications
Accumulator	Large volume size, standard flowrate
Hydraulic motor	Electric variable displacement control
PRB control valve	Electric flow control
Accumulator valve	Electric flow control

Table 1: PRB hydraulic components

For the rapid-prototyping software development, the National Instruments' compact RIO was chosen to the main controller, the control algorithm was come from the simulation model developed by MATLAB Simulink. It was necessary that there should be interfacing development tool between National Instruments' hardware and MATLAB software. The National Instruments' software tool, Veristand was an appropriate tool for this multi-platform interfacing, real-time calibration and monitoring. **Figure 7** shows the overall control system setup.

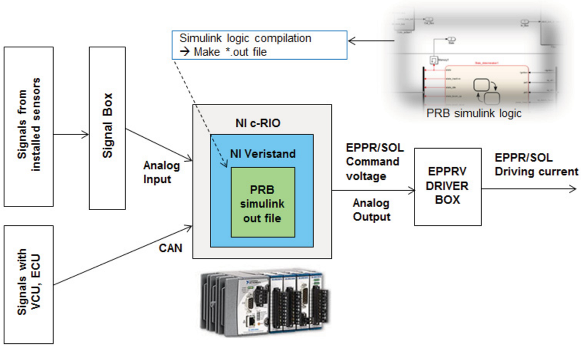

Figure 7: Overall control system setup for the PRB verification on real machine

With PRB installed 38ton excavator, we carried out the fuel consumption evaluating test by performing the repetition of a general digging and dumping load cycle with 180 degrees swing. Test target is comparison of PRB operating condition with PRB no-operating condition which is same as VBO system. **Figure 8** was a picture taken during the fuel consumption test. In order to record the very exact fuel consumption rate, a certified accurate fuel meter was also installed onto excavator during the test cycle.

Figure 8: PRB installed 38ton excavator testing, Doosan's DX380LC-3

We had analyzed the measured cycle data, checked the recorded values from the certified fuel meter. We found that the fuel consumption of PRB operating test case was dramatically decreased by 5.0 L/hr compared to PRB no-operating test case. **Figure 9** shows the part of analyzed data with PRB operating test condition. During boom down motion, pressurized oil which exists in the boom cylinder head chamber goes to the accumulator and the hydraulic motor simultaneously by controlling the PRB control valve, the accumulator valve and the swivel angle of the hydraulic motor electrically. The hydraulic motor is generating the output torque by a high pressure oil flow and this torque is assisting diesel engine connected by PTO (Power Take-Off). The diesel engine controls the rotating speed of the crank shaft; therefore due to assist torque from hydraulic motor, the fuel injection rate is decreased by the speed control of Engine control unit. *[CHG phases]* After the boom down motion, the accumulator is already charged by a high pressure oil flow and an electric PRB controller opens the accumulator valve and controls the swivel angle of the hydraulic motor. It means that the charged oil of the accumulator goes to the hydraulic motor, leads to generate assist torque to the diesel engine. Therefore, also fuel injection rate is decreased. *[DCG phases]*

Of course, the fuel saving mentioned above is related to the pattern of excavator's boom operating. For example, a leveling operation of ground shows very little portion of boom motion (small stroke of boom cylinder), it means that there is no potential energy of boom. The meaningful fuel saving cannot be achieved. However, a digging and dumping cycle is very usual and standard working cycle of excavator, and this paper shows the success of decreasing of fuel consumption.

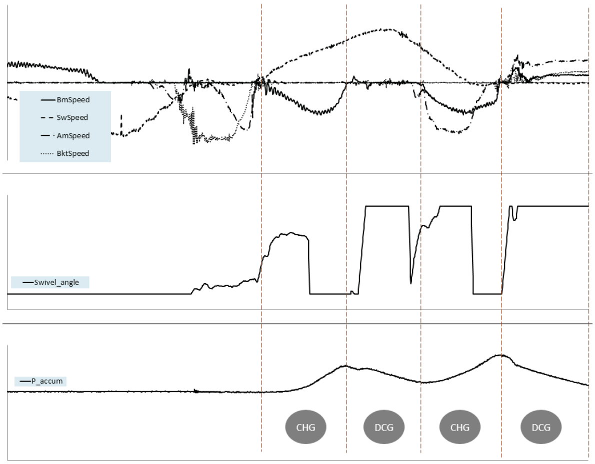

Figure 9: PRB operating condition test data of digging and dumping load cycle

Besides fuel saving performance, the controllability performance is also a very important factor for the customer satisfaction. If the customer feels any difficulties of controlling the working cycle, it is leading to slumps of market sales. Professional operator did the controllability evaluation and the result said that the controllability performance of PRB system is almost similar to the VBO standard excavator during the digging and dumping operation, although some amount of motion delay of stopping boom down motion and very fine movement of down should be improved. Doosan Infracore has a plan to improve further precise controllability of PRB with the cooperation of Bosch Rexroth in the very near future.

5. Conclusion

We have successfully developed the hydraulic hybrid system for excavator. The system concept design and the model based verification was done by a virtual excavator model, and we carried out the performance test of PRB system with 38ton excavator. The actual machine result showed that fuel consumption was decreased by 5.0 L/hr, also having almost same controllability during digging and dumping operation compared with standard VBO excavator model, DX380LC-3. Both companies are now improving PRB system together regarding further fuel saving possibilities, cost optimization and fail-safety & functional-safety design.

6. References

/1/ Bosch Rexroth official webpage, Press release of 032-13, http://www.boschrexroth.com/en/xc/company/press/index2-2564

/2/ Caterpillar official webpage, products of 336E H, Benefits and Features, http://www.cat.com/en_US/products/new/equipment/excavators/large-excavators/18378156.html

/3/ Komatsu official webpage, Press release of 2008/05/13, http://www.komatsu.com/CompanyInfo/press/2008051315113604588.html

/4/ Jan Amrhein & Uwe Neumann. 2012. International Fluid Power Conference, "PRB - Regeneration of potential energy while boom-down"

/5/ Bender, F.A., Sonntag, M., and Sawodny, O. Nonlinear model predictive control of a hydraulic excavator using Hammerstein models. The 6th International Conference on Automation, Robotics and Applications (pp. 557-562). IEEE, 2015.