CONTROL SYSTEM OF HYDRAULIC RECOVERY MODULE OF ROAD ROLLER

JOSEF NEVRLY[1], ZDENEK NEMEC[2], JAN BRANDEJS[1]
[1] Institute of Machine and Industrial Design,
Faculty of Mechanical Engineering, Brno University of Technology
Brno, Czech Republic,
[2] Institute of Automation and Computer Science,
Faculty of Mechanical Engineering,
Brno University of Technology
Brno, Czech Republic

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e-mail: nevrly@fme.vutbr.cz

This paper briefly describes some features of control of the hydrostatic recovery module developed within the framework of a research project. This project was focused on research and development of a new product – a hydrostatic system for energy recovery through breaking and start-up of commercial vehicles using control for energy transfer and optimization based on mathematical modeling of the system activity. A contribution of described solution of control system of hydraulic recovery module of the road roller can be seen in the fact that this solution enabled fuel savings during recovery up to 26.6 % at low operation speed of 9 km/h.

KEYWORDS
control, energy, recovery, hydrostatic, module

1. INTRODUCTION

The hydrostatic recovery module for energy recovery through braking and start-up of commercial vehicles was proposed and created at first in the form of an experimental model on which a mathematical-physical analysis was carried out; corresponding mathematical models of energy recovery courses were created. Results received by means of this activity were transferred to the proposed hydraulic recovery module of the real commercial vehicle where the testing equipment with energy transfer optimization was realized. The international project was solved by Brno University of Brno in cooperation with the German company Bosch Rexroth and the Swiss company AMMANN.

Prior to our research, literature search was performed [Nevrly 2011] where, in available sources e. g. [Delafosse 2012], [Kanber 2003], [Matheson 2003], no successful solution to kinetic energy recovery of braked vehicle at low speed (in our case it is maximum of 9 km/hour) was found. For example, the test protocol of the company Bosch Rexroth (quoted in [Nevrly 2015, p. 14]) introduced the result of their research carried out together with the Swiss company AMMANN before the year 2012 using the road roller AMMANN AP 240 H: "No fuel was saved". Afterwards, we carried out our research using the same road roller AMMANN AP 240 H. During our research of the hydraulic recovery module, an experimental stand was developed and used. A description of its design and results are beyond the scope of this paper and can be found e. g. in [Klapka 2014], [Nevrly 2013b], [Nevrly 2014a], [Nevrly 2016] [Pourmovahed 1992a], [Pourmovahed 1992b].

This paper does not make any claim to completeness and continuity because it is only a sketchy outline of solutions to some selected problems. A more detailed description can be found in the quoted research reports, articles and other published and unpublished materials of researchers of the three-year international project.

2. BASIC PARAMETERS OF ROAD ROLLER AMMANN AP 240 H

The road roller AMMANN AP 240 H [Nevrly 2013a], a product of the Swiss company AMMANN, was chosen as an experimental vehicle. This machine was provided by this company for research purposes. It is a roller used for finishing of road surfaces. A structure of the roller has a basic frame of modular type on which the driver´s cabin is situated, an internal combustion engine and space for a ballast reservoir.

Figure 1. Road roller AMMANN AP 240 H

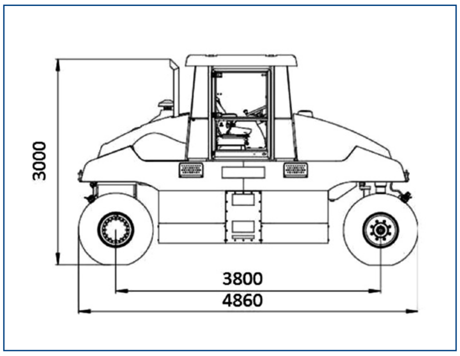

Figure 2. Basic dimensions of the roller

The mass of the vehicle was 9350 kg, with possible additional mass up to 24 000 kg. Maximum admissible transport speed of the vehicle is 19 km/h and maximum operating speed is up to 9 km/h. The conception of the vehicle enables 20 hours of continuous operation of the machine. The roller drive was realized by means of hydraulic circuit driven by diesel engine Cummins 4BT4.5-C99, power of 74 kW. A hydraulic recovery module was created for recovery of kinetic energy of a road roller (Fig. 1, Fig. 2). The module was connected to the existing hydraulic system of the roller by means of hoses. The electronic part was situated in the cabin of the driver in a separated distributor board. The basic scheme of the recovery system is illustrated in Fig. 3.

3. SCHEME OF HYDRAULIC CIRCUIT OF THE ROLLER

In order to minimize interventions in the tested road roller AP 240 H, its original control was preserved, and for the purpose of recovery the control was extended using an auxiliary unit ECU (Electronic Control Unit) [Nevrly

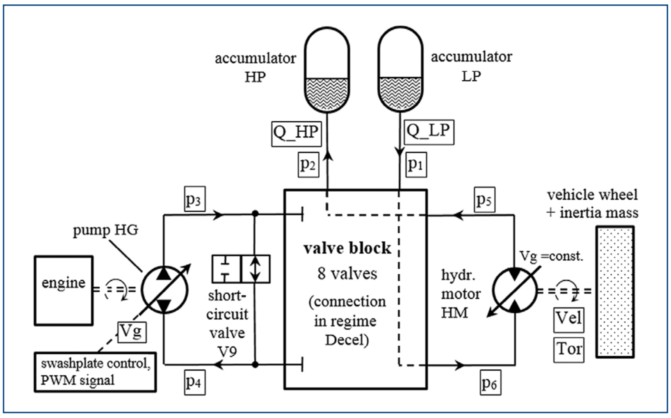

Figure 3. The basic scheme of the recovery system

2015a]. The original control system was based on the software DRCE (Drive Control E) from the company Bosch Rexroth. The extended control unit ECU was adapted to the hardware designated for the applications on mobile machines equipped with the products of the company Bosch Rexroth. It was hardware of new generation RC 28–14 /30 with 32-bit processor. Software for recovery control module was based on the experience gained from experimental stand [Delafosse 2012], [Nevrly 2013b] built in the previous phase of the project. The program was created in the language which is a standard used for programmable automats.

4. THE MAIN REGIMES OF ROLLER

The schemes of hydraulic circuit of the roller with the hydraulic recovery module can be seen in Fig. 4 and Fig. 5 [Nevrly 2014b]. A diesel engine driving the pump which delivers pressurized oil to the hydraulic circuit can be seen in the figures on the left. This oil then drives two hydraulic motors of the drive (in the figure on the left). The hydraulic recovery module was connected to the existing hydraulic circuit of the roller as an auxiliary equipment. The valve control block can be seen in the figure inside the dashed rectangle.

The regime **DECEL** finds its use during braking of the roller and represents the main regime for energy recovery. In this regime, a high pressure hydraulic accumulator is attached to the hydraulic circuit. This accumulator is able to accumulate a certain amount of energy and store it for later use during acceleration. Redirecting of the medium flow is carried out in the distribution block by means of a suitable connection of valves. Disconnection of the pump is performed by valve setting. A simplified scheme of the regime DECEL is in Fig. 4.

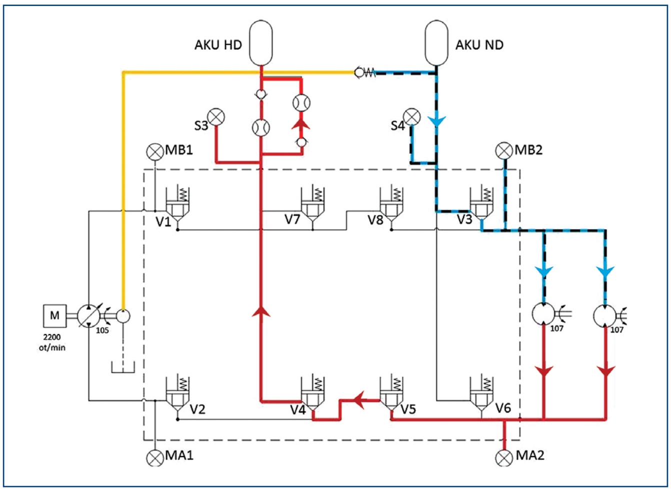

Figure 4. Regime DECEL – braking

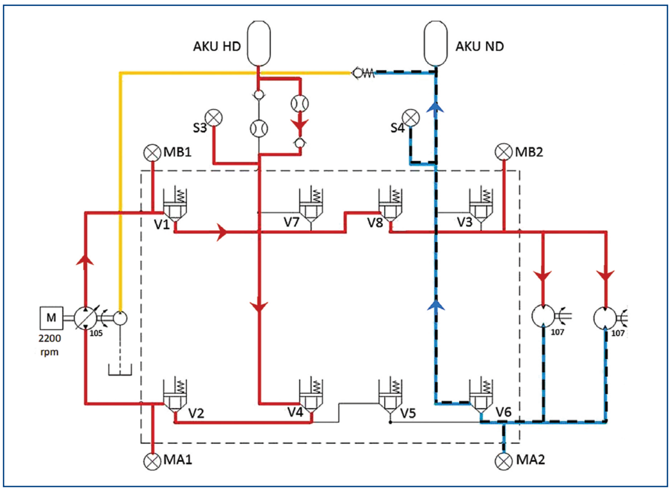

Figure 5. Regime ACCEL – acceleration

The regime **ACCEL** (Fig. 5) determines the acceleration of the roller up to its constant speed. A diesel engine drives a pump which distributes the energy to the two hydraulic motors by means of pressurised oil. The recovery system connected through a distribution block is included into the existing hydraulic circuit. Proper connections between the individual valves enabled us to deliver the saved energy from the high pressure accumulator into the pressure part of the circuit (mostly the left part) for acceleration of the roller, thus lowering the energy claimed from the diesel engine to save the fuel.

A further operation regime is an idle run – FREE RUN. No change of accumulated energy takes place during this regime, the output of the combustion engine is consumed only for vehicle drive. Regimes and possible transitions are referred to in Fig. 9.

5. MODELING OF SYSTEM

Modeling of the road roller and its control was carried out in Matlab/Simulink/SimScape [Kanber 2003], [Nemec 2016], [Nevrly 2015a], [Zavadinka 2012]. An important part of control was especially the control of valves carried out by a control unit; in our model, control is an imitation of subsystems according to the scheme in Fig. 6 ([Nevrly 2015a], p. 43). 16 delay elements were used in the model of valve control, which considerably destabilized and prolonged simulation computations.

A significant advantage of designed models is their modularity. Every model is a system of subsystem blocs with different functions arranged hierarchically in several levels (Fig. 6 shows a structure of basic level) [Nemec 2014]. In this way, universality is reached and it is easy to realize modifications of simulation activities.

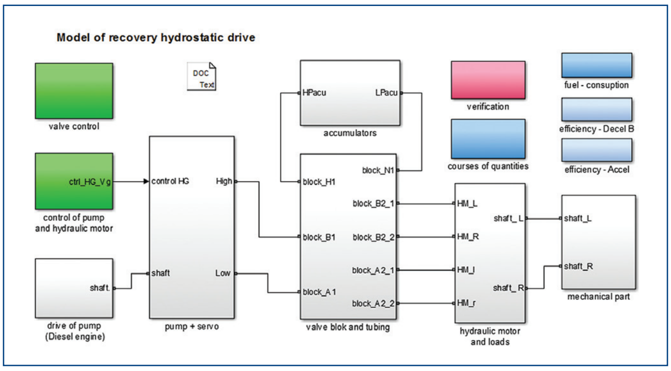

Figure 6. Wholesale scheme of the model of the road roller with the hydrostatic drive

An example of solution to the control block is in Fig. 7 [Nemec 2014]. Suitable control and timing of valves is a basic condition for successful function of recovery. It was necessary to create a proper timing of valves to reach a good efficiency and effectiveness as well as to eliminate the undesirable states, e. g. hydraulic short circuits, etc. An example of time courses as a result of simulation can be seen in chapter 6.

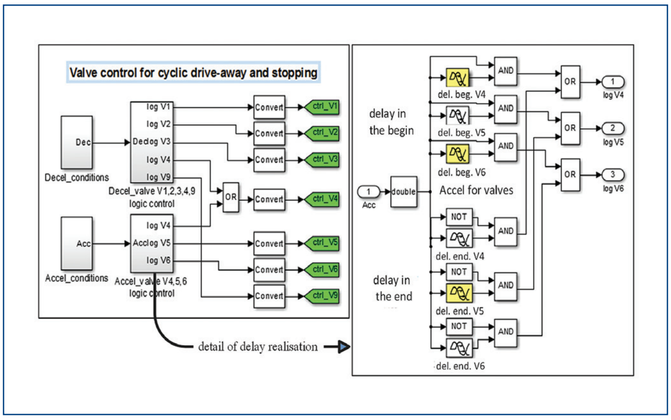

Figure 7. Model of valves control

6. CONTROL SYSTEM OF THE RECOVERY MODULE

In order to minimize interventions in the tested road roller AP 240 H, its original control was preserved, and for the purpose of recovery the control was extended using an auxiliary unit ECU (Electronic Control Unit). The original control system was based on the software DRCE (Drive Control E) from the company Bosch Rexroth. The extended control unit ECU was adapted to the hardware (HW) designated for the applications on mobile machines equipped with the products of the company Bosch Rexroth. It was hardware of new generation RC 28–14 /30 with 32-bit processor. Software for recovery control module was based on experience gained from the experimental stand [Nevrly 2013a], [Nevrly 2013b] built in the previous phase of the project. The program was created in the language which is a standard used for programmable automats.

6.1. Function of control system of recovery structure

A simplified scheme of control system for hydrostatic powertrain is described in Fig. 8. The main inputs and outputs of the electronic control unit are shown there. The original system is in the upper part of the scheme – for the diesel engine and the hydrostatic pump. Both of them are controlled by ECU. The diesel engine is controlled via CAN bus (the engine has the second ECU) and the hydrostatic pump is controlled via PWM signal to the solenoids. Inputs for control of the diesel engine and the hydrostatic pump go from the throttle (processed in ECU with ramps and limits) and the direction switch.

The lower part of the scheme shows the second ECU for the hydrostatic recovery module. There are digital outputs to the valves on the valve block. These signals are processed by the state machine in ECU according to these inputs – the speed sensor, the pressure sensors on the accumulators, signal to the hydrostatic pump and the switch. This switch turns on and off the recovery module ([Nevrly 2015a]).

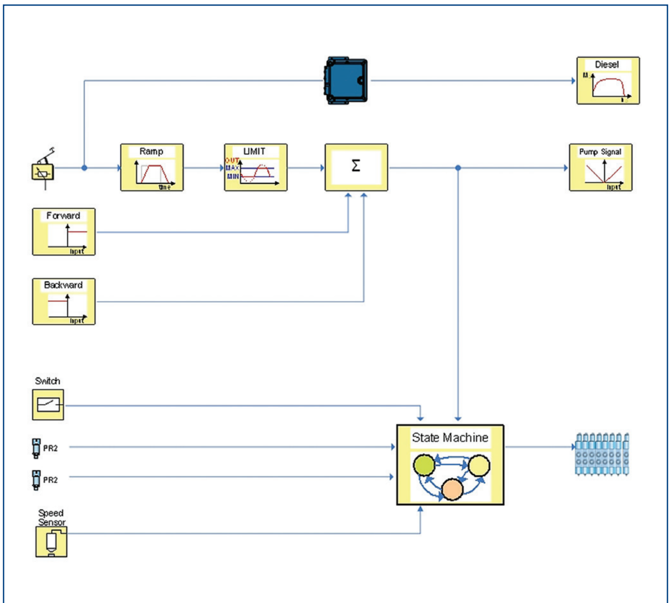

Figure 8. Scheme of the control system [Nevrly 2015a]

Fig. 9 shows three basic movements of vehicle depicted (central rectangles) – Vehicle acceleration, Vehicle deceleration (braking), and moving with constant speed (constant speed moving) named as FREE RUN. The term Free run was chosen because the vehicle in this mode moves without using accumulators. Oil flows directly through the valve block.

Between these three movements there are four transitions (side rectangles) ACCEL, ACCEL to FREE RUN, DECEL and DECEL to FREE RUN. The control system selects the correct one based on input conditions (vehicle speed, diesel engine rpms, pressures in system, throttle change). Transition from FREE RUN to Vehicle acceleration is called ACCEL, a return back is ACCEL to FREE run. Changes between FREE RUN and Vehicle deceleration are DECEL and DECEL to FREE RUN. For each transition, specific sequence of valve switching is defined ([Nevrly 2015a], p. 77).

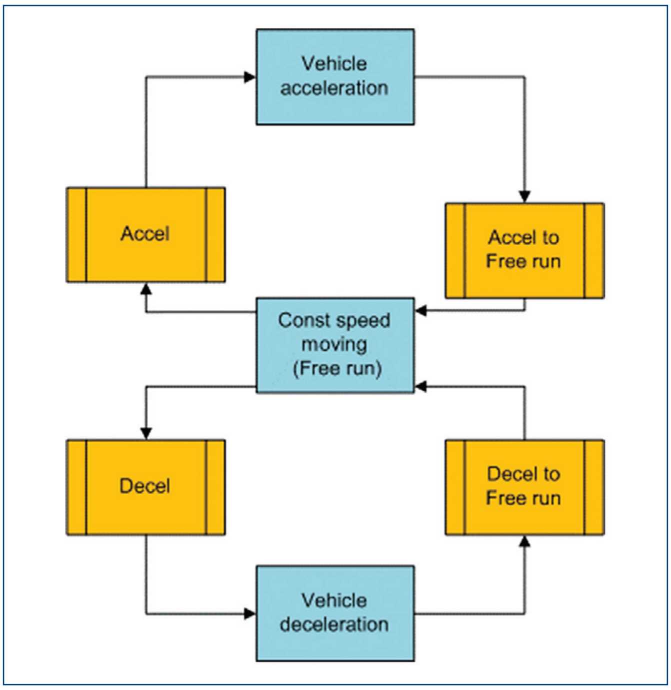

Figure 9. Vehicle states and transition states of the recovery structure

6.2. Control of pump

The pump was controlled by a gas pedal. The gas pedal was used both for control of speed of diesel engine and also for control of changes of geometric volume (Vg) of the travel pump. Control of speed of diesel engine was not an integral part of the control system of the recovery superstructure. A signal to pump was modified by time ramp. This ramp served for prolongation of pump reaction on the change of the input signal (gas pedal).

The time ramp given in ms determined the time interval of change of output signal from Vg min to Vg max at jump change of the input signal from 0 % to 100 %. This basic principle of pump control was used for regime FREE RUN. For other regimes, it was necessary to further modify the time course of the signal.

7. VERIFICATION OF DESIGNED CONTROL

A comparison of simulation and measurement results realized in the road roller was an important support for recovery control design. Without measurement, it would not be possible to create reliable models because a number of important parameters of vehicle would not be available. From this point of view, the most difficult task was to create a model of pump and combustion engine control. An example of this procedure is in Fig. 10.

Time courses of relevant and chosen quantities show a sufficient credibility of the model and its applicability for the given purpose. Differences found for less important quantities are not substantial and can be explained. Correctness and effectiveness of designed solution was proved by numerous tests on the adapted road roller during measurements of its fuel consumption; savings were up to 26.6 %.

Novelty and benefits of our research lie in the fact that energy recovery was realized in the vehicle working at low operation speeds (up to 9 km/h) where the up-to-now attempts worldwide were not successful. Some hydraulic parts of recovery equipment can be seen in Figs. 11 and 12.

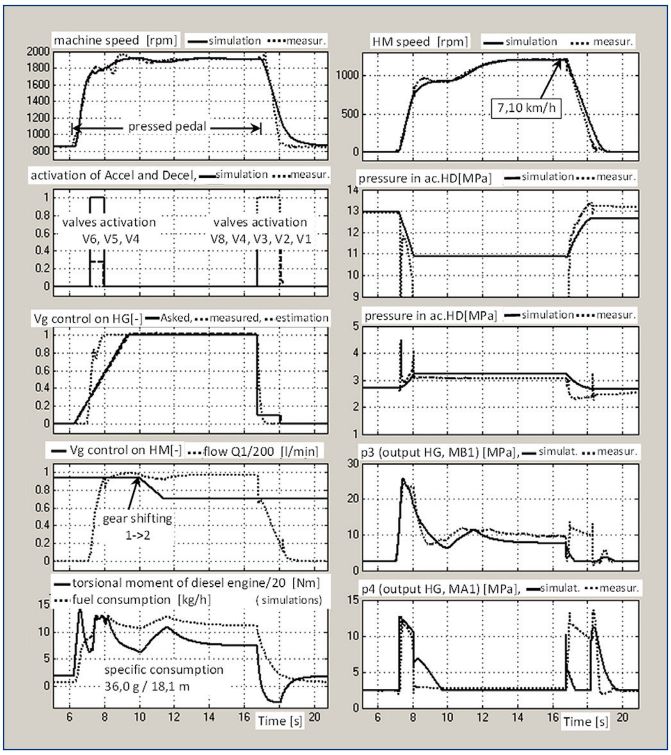

Figure 10. Comparison of simulated and measured quantities

Figure 11. Some hydraulic parts of hydraulic recovery equipment

Figure 12. Road roller Ammann AP 240H equipped with hydraulic recovery module

8 SUMMARY AND CONCLUSION

Control of the hydrostatic module to drive a particular road machine is so complex that its solution was divided into design and realization phase on the experimental laboratory stand and only after that on a real machine. A significant support for design and analytic activities was the use of computer models and simulation. This consisted in creation of sufficiently detailed models of the drive and the following simulations to examine the properties of individual design solutions. The order of state changes of valves is substantial for a smooth course of regimes ACCEL and DECEL – time opening and closing of valves is not symmetrical. Every valve was enabled to have an adjustable delay towards the start of the respective regime. The main problem of the system optimization was to find ideal parameters for transition states in hydrostatic system. For this reason, it is necessary to distinguish between the drive state of vehicle (acceleration, movement at constant speed, braking) and transition states between these drive states.

A contribution of described solution of control system of hydraulic recovery module of the road roller can be seen in the fact that this solution enabled fuel savings during recovery up to 26.6 % at low operation speed of 9 km/h. Fuel consumption was measured during the roller drive on a 18.5 m long, straight, horizontal route with smooth concrete surface ([Nevrly 2015a], pp. 68-72).

Operation ecology and brake wear were also improved The developed hydraulic recovery module with originally created control enables a substantially more efficient operation of commercial vehicles with hydrostatic drive and start-stop regime, working at low speeds up to 9 km/hour as it is e.g. in the case of road rollers. Uniqueness of this system can be seen in the effective coverage of the low-speed region and considerable fuel savings.

This was possible due to the design and use of the experimental stand, computer modeling, optimization by means of differential evolution algorithms [Panacek 2014] and control experiments [Nevrly 2015a] on the experimental vehicle.

A further continuation of our research can be focused on working out of developed methods in detail, creation of analogical control systems for other suitable types of commercial vehicles with cyclic start-stop operation regime. The developed methods can also be used for solution to further problems; nowadays e. g. we apply them in a modified form to solve the project TRIO (sponsored by the Ministry of Industry and Commerce) of drive control of an excavator driven only by electric accumulators. This equipment, together with the control unit of hydraulic recovery module, was exhibited at this year's MSV – International Engineering Trade Fair in Brno where, in last years, we demonstrated "a hydromobile" – a special experimental vehicle equipped with energy recovery developer parallel with our research of the hydraulic recovery module and its control.

Acknowledgment

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Contacts:
Prof. Dr. Ing. Josef Nevrly, Ph.D.
Ass. Prof. Ing. Jan Brandejs, Ph.D.
Institute of Machine and Industrial Design
Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 54114 3254, email: nevrly@fme.vutbr.cz
tel.: +420 54114 3254, email: brandejs@fme.vutbr.cz
http://uk.fme.vutbr.cz/

Ass. Prof. Ing. Zdenek Nemec, Ph.D.
Institute of Automation and Computer Science
Brno University of Technology, Faculty of Mechanical Engineering
tel.: +420 54114 2299, email: nemec@fme.vutbr.cz
http://uai.fme.vutbr.cz/