Hybrid Drives for Mobile Equipment

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Abstract

A clear reduction in diesel fuel consumption of up to 25 percent in heavy commercial vehicles and correspondingly fewer exhaust emissions are achieved by the newly developed HRB Hydraulic Regenerative Braking System from Rexroth. This is verified in practical testing and field trials with a waste collection truck built by Haller Umweltsysteme GmbH & Co. KG and in service with the Berlin Sanitation Department. The vehicle has been proving its worth in everyday use since July of 2008. Actual measurements confirm the simulation-calculated savings. Software developed by Rexroth allows vehicle manufacturers to perform economy calculations in advance.

Keywords: Emissions reduction, hydraulic hybrid, hydrostatic regenerative braking system, mobile construction equipment, commercial vehicles, reduced consumption
1 Introduction

Waste collection vehicles, school and city buses as well as mobile construction equipment and heavy commercial vehicles, all of which are characterized by frequent stopping and starting, also generate significant braking energy. This increases the diesel fuel consumption and along with it emissions of exhaust gases. The Hydrostatic Regenerative Braking system from Rexroth stores the energy from conventional braking which is converted into useless heat and makes it available for acceleration. This system solution uses the high power density of the hydraulics for highly efficient recovery of the braking energy. As a result, the load on the combustion engine is reduced during acceleration and less exhaust gases are generated since the overall fuel consumption is lowered.

2 The Hydrostatic Regenerative Braking System

The parallel hybrid drive is ideal for vehicles having a conventional mechanical drivetrain and a combustion engine. A hydraulic axial piston unit coupled to the mechanical drivetrain through a gearbox converts kinetic braking energy into hydraulic energy. The axial piston unit acts like a pump and fills a hydraulic membrane type accumulator with hydraulic fluid. This process is controlled by an electronic unit made by Rexroth in conjunction with a hydraulic valve control block (Fig. 1).

![Fig. 1: System components of the HRB parallel: A4VSO axial piston unit with gearbox, pressure accumulator, accumulator safety relief valve, HIC valve control block, electronic controller](image)
During acceleration the entire process is reversed: the pressurized fluid is evacuated from the accumulator in a controlled manner and flow back through the axial piston unit. The latter is driven by the fluid flow and, acting like a motor, transmits its power to the mechanical drivetrain. This takes the load off the engine and thereby reduces fuel consumption. A positive side effect for the vehicle operator is significantly less brake wear thanks to HRB. The fine dust production caused by brake wear and CO\textsuperscript{2} emissions from the combustion engine are correspondingly reduced.

The modular construction means the HRB parallel can be integrated into virtually any common vehicle frame. Retrofit kits for existing fleets could also be offered by the vehicle manufacturer. The system solution consists of semi-standard components from Rexroth’s hydraulics and electronics product lines.

3 The trial vehicle

Since July of 2008 the Berlin Sanitation Department has been field testing a series x2eco waste collection vehicle made by HALLER Umweltsysteme GmbH & Co. KG fitted with a Rexroth parallel hybrid (Fig. 2). The vehicle is based on a Mercedes-Benz Actros chassis with a permissible gross weight of 26 tons. The large-series drive motor achieves 235 KW at 1800 rpm with a torque of 1650 Nm in combination with an automatic 16-gear transmission. The installed HRB uses two membrane type accumulators with a capacity of 32 liters of nominal gas volume each and a maximum accumulator pressure of 330 bar. This means the accumulator achieves a capacity of 550 kilojoules (approx. 0.15 kWh) and control an acceleration torque of up to 2500 Nm. The HRB speed range is from 0 to 43 km/h. The compact individual components weight a total of around 500 kg.
4 Individual system configuration

To configure the HRBG in the trial vehicle and to calculate the possible diesel fuel savings Rexroth used a combination of simulation programs for vehicle development, Matlab/Simulink, as well as the AMESim simulation environment designed especially for the unique physical characteristics of hydraulics. From this the application specialists at the hydraulics manufacturer calculated the sizing of the individual components specifically for the vehicle land its driving cycle.

The model verified for the trial vehicle first calculates the energy which can be stored and the specification for desired braking effect. The simulation takes into account the vehicle mass, the desired maximum speed as well as the rolling resistance, the efficiency of the mechanical HRB components and the vehicle drivetrain used by the HRB. Additional factors such as drive motor drag torque, air resistance and the energy requirement of the ancillary vehicle systems which need to be driven during braking.

$$E_{\text{reg}} = (E_{\text{kin}}-E_{\text{roll}}-E_{\text{air}}-E_{\text{drag}}-E_{\text{ancillary}}) \times \eta_{\text{mh}} \times \eta_{\text{drive}}$$
Membrane type accumulators are used for storing the energy. The membrane is filled with nitrogen and is kept under a defined charging pressure. Assuming an adiabatic state change the calculation of the required accumulator size is calculated as follows:

\[ V_{\text{accumulator}} = E_{\text{reg}} \cdot \left[ \frac{n-1}{p_i} \cdot \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \]

In a second step the axial piston unit is configured. The required braking torque results from the vehicle data and the desired braking.

\[ T_{HRB} = (m \cdot a \cdot d / 2 - T_{\text{roll}} - T_{\text{air}} - T_{\text{drag}} - T_{\text{ancillary}}) \cdot \frac{\eta_{\text{drive}}}{i_{\text{Differential}}} \]

The braking torque received by the axial piston unit in pumping mode is the essential determining factor in the generated torque. It results from the product of the momentary pressure, which is assumed to be the average accumulator pressure \( p_M \), and the flow rate of the axial piston unit. The flow rate \( v_G \) of the axial piston unit and the HRB gear ratio \( i_{HRB} \) is calculated as:

\[ i_{HRB} \cdot v_G = \frac{T_{HRB} \cdot 100 \cdot \eta_{mh}}{1.59 \cdot p_M} \]

Configuration of the flow volume for the axial piston unit must take into account that the permissible speed of the axial piston unit at the given maximum speed of the vehicle is not exceeded while the HRB is in operation.

### 5 Simulation and calculation of fuel savings

Software developed by Rexroth enables the designers to estimate in advance what the possible fuel savings potential is for the selected vehicle with given driving cycles. The tool uses the speed curve and vehicle mass to calculate the power present at
the wheel (Fig. 3). Drive and braking power values are shown as gray areas. The portion of the power which can be recovered by the HRB is shown in green.

![Diagram](image)

**Fig. 3:** Simulation of the HRB contribution to the drive and braking power values.

The software takes into account the efficiency of the axial piston unit and the HRB drive and calculates the amount of hydraulic energy which the system converts from the mechanical braking energy at the HRB drive shaft into hydraulic energy. At the same time it determines how much mechanical drive energy the stored hydraulic energy creates at the HRB drive shaft during acceleration. Depending on the configuration, vehicle and driving cycle, the system achieves total conversion rates of well over 60 percent. This load which is relieved from the diesel motor results in significant fuel consumption savings. Addition cost savings in the form of reduced brake wear increase the overall economy even more.

Before the HRB system was put into operation on the trial vehicle, Rexroth optimized the control and regulation using comprehensive simulations (Fig. 4). Here the developers identified in advance any possible weaknesses in the system. During the entire field trial with various test sequences and parameter changes, a data logger recorded all error messages. To ensure correct conversion of the functions into C-code, the software specialists created a reliable SIL environment within the Co simulation.
6 Practice confirms the simulation

With the help of the simulation both the vehicle manufacturer and the operator were able to calculate the possible savings and estimate the ROI time for various driving cycles (Fig. 5).
These calculations are based on collection cycles for a half-loaded garbage truck. The simulation depicts the essential effects of the HRB and uses the reduced consumption to show a key ergonomic benefit for the crew: no interruption in acceleration force when shifting up through the gears.

Rexroth verified these simulation results on the test vehicle in a wide range of tests under controlled conditions. Table 1 shows the comparison of the simulation values and the actual consumption values measured under test conditions with a 100 m cycle. The deviations of the simulation from the determined test consumption values are less than 4 percent. This means the simulation is capable of providing reliable predictions for possible fuel savings with the HRB system.
Table 1: Comparison of the simulated and measured consumption.

<table>
<thead>
<tr>
<th></th>
<th>w/out HRB absolute [l]</th>
<th>with HRB absolute [l]</th>
<th>Savings absolute [l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>0.111</td>
<td>0.080</td>
<td>0.031</td>
</tr>
<tr>
<td>Measurement</td>
<td>0.108</td>
<td>0.077</td>
<td>0.032</td>
</tr>
<tr>
<td>Deviation</td>
<td>2.78 %</td>
<td>3.90 %</td>
<td>-3.13 %</td>
</tr>
</tbody>
</table>

The test series encompassed different driving cycles. Pylons set up at defined intervals on a circular course simulated the distance between trash cans. For the measurements the distance was varied from 10 to 70 and 100 meters (Table 2). The driver stopped at each pylon for 30 seconds to simulate emptying of the cans. The weight of the vehicle was a uniform 20 tons for all trials. Multiple repeat cycles provided reliable savings figures, obtained with a type KMA fuel measuring system, of between 16 and 30 percent.

Table 2: Average savings in tested collection cycles.

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>Weight [kg]</th>
<th>Stop time [s]</th>
<th>Drive time [s]</th>
<th>Consumption per stop with HRB [l]</th>
<th>Consumption per stop w/out HRB [l]</th>
<th>Savings per stop [l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20000</td>
<td>30</td>
<td>7</td>
<td>0.021</td>
<td>0.025</td>
<td>0.004 (16%)</td>
</tr>
<tr>
<td>70</td>
<td>20000</td>
<td>30</td>
<td>16</td>
<td>0.059</td>
<td>0.079</td>
<td>0.020 (25%)</td>
</tr>
<tr>
<td>100</td>
<td>20000</td>
<td>30</td>
<td>22</td>
<td>0.076</td>
<td>0.108</td>
<td>0.032 (30%)</td>
</tr>
</tbody>
</table>

The field trial cannot provide these controlled conditions, since even given identical driving routes different traffic situations and trash loads on different days lessen the comparability. But the initial results show that the savings for the respective driving cycles lie within the simulation results and the controlled test series.
The focus of the field trial begun in July 2008 is on testing the suitability for everyday use and reliability of the HRB system, since the savings in fuel consumption have already been verified. During the first six months until the press deadline for this article the HRB system functioned with no appreciable failures, providing an up-time of nearly 100 percent. Membrane type accumulators are intrinsically low-maintenance, affected essentially by the charging pressure and condition of the membrane. The hydraulic fluid serves not only to transfer the power, but also lubricates the axial piston unit. Permissible hydraulic fluid temperatures are in a range from -20° to +80°C. The vibration-resistant and up to 25g shock-resistant control electronics has a high electromagnetic compatibility of 100V/m and can communicate with other systems via CANbus.

The HRB is virtually temperature-independent when the permissible viscosity ranges are observed and under consistent power density. Even at high summer ambient temperatures of up to 35°C the hydraulic fluid remains reliably within the optimal temperature window even given very short cycles. One strength of the hydraulic hybrid drive: even low temperatures have a negligible effect on the energy storage and power density of the HRB.

During testing it turned out that the additional available drive torque of up to 2500 Nm allows the vehicle to take off in third gear on level ground. The gear changes no longer involve an interruption in motive force (Fig. 6). In addition to the greater driving comfort thanks to jerk-free acceleration, further economic advantages result from transmissions with fewer gears or smaller engines.
8 Outlook

The HRB system is proving itself in field trials with the Berlin Sanitation Department as a technically reliable module which significantly reduces fuel consumption. It achieves the savings calculated in simulations and validated in test series. Software developed by Rexroth can realistically depict the drop in consumption for different driving cycles even before actual integration. This means both the vehicle manufacturer and operator can very precisely calculate the ROI time. The tool thereby assists the operator in optimizing the deployment and route schedules.

Beyond the start of series production for the HRB in its current configuration, Rexroth is hard at work on the development of other hydraulic recovery systems. The developers are looking particularly at hydrostatic transmissions and working hydraulics in mobile applications.