DEVELOPMENT OF A HYDRAULIC DRIVE FOR A NOVEL HYBRID DIESEL-HYDRAULIC SYSTEM FOR LARGE COMMERCIAL VEHICLES

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ABSTRACT

The objective of the research project, the subject of this paper, is to develop a hybrid diesel-hydraulic drive for large commercial vehicles e.g. urban freight delivery, buses or garbage trucks. The system incorporates a Regenerative Drive Shaft (RDS) which consists of a variable pump/motor coaxial with the drive shaft. Hydraulic energy is supplied to the wheels of the vehicle in parallel with energy supplied by the truck drive system. The objective is to store/supply energy to assist truck braking/acceleration. The unit works as a pump during braking of the truck and thus performs two functions - it stores energy in the accumulator and at the same time provides hydrostatic braking. When the truck accelerates the pump operates as a motor assisting the truck engine. The major advantages of the proposed RDS system over other systems is the application of microprocessor control to optimise power utilisation and elimination of losses during transfer of energy between the truck drive system and the hydraulic pump/motor. This technology offers additional advantages of lower noise, increased reliability, lower maintenance costs and a substantially reduced environment impact. The paper presents and discusses the development of the system, modelling approaches and the results of preliminary performance tests on 10 ton vehicle.

KEYWORDS

hydraulic, hybrid, vehicle, regenerative, braking

INTRODUCTION

Hybrid drive systems for passenger and commercial vehicles were and still are undergoing extensive development with almost exclusive concentration on electric hybrid drives. Hydraulic hybrid drives, mostly using various arrangements of hydrostatic drives in conjunction with mechanical energy storage (flywheels), were proposed in the past by various companies and Universities without much commercial success, although some of the system were installed in city buses, [1-10]. A notable development in this field was Volvo Cumulo hybrid system, which was tried on city buses in the mid eighties. Cumulo system consisted of pump/motor and hydraulic energy storage, the hydraulic unit was coupled to the drive shaft via a transfer gearbox, [11]. The perceived disadvantages of hybrid drives, low efficiencies of hydrostatic drives, weight, and control problems, led
The interest in hydraulic hybrid was recently revived by the development of the Permo-Drive Regenerative Energy Management (PDREM) System and recent announcement by a major car manufacturer of a project to develop a hydraulic hybrid drive for an utility vehicle.

The objective of the R&D project, the subject of this paper, is to develop a hybrid diesel-hydraulic drive for large commercial vehicles e.g. urban freight delivery, buses or garbage trucks. The major advantages of the PDREM System over other systems proposed in the past is a marked reduction in losses during transfer of energy between the truck drive system and the hydraulic pump/motor and in application of microprocessor control to optimise power utilisation. This technology offers additional advantages of lower noise, increased reliability, lower maintenance costs and a substantially reduced environment impact. The paper briefly describes the RDS system and the application of simulation models for hydraulic control and drive systems. The results of some performance tests on 10 ton vehicle.

**THE RDS SYSTEM**

The PDREM System is shown in Figure 1. The "heart" of the system is Regenerative Drive Shaft (RDS) unit, shown in Figure 2, which consists of an axial piston pump/motor coaxial with the drive shaft and a manifold block which houses the control system. Hydraulic energy is supplied to the wheels of the vehicle in parallel with energy supplied by the truck drive system. The system stores energy during the retardation cycle and supplies energy during the propulsion cycle to assist truck deceleration/acceleration. The RDS unit works as a pump during the retardation cycle and performs two functions - it stores energy in the pneu-hydraulic accumulators and at the same time provides hydrostatic braking. When in propulsion mode the RDS operates as a motor assisting the engine. The retardation and propulsion torques are controlled by changing the position of the swash plate. The electronic management of the retard/propulsion cycles makes it possible to optimise energy delivery to the truck wheels. The required position of the swash plate is controlled by an electronic control system in response to inputs from vehicle systems (engine, gearbox, brakes) and environment (speed requirement, road elevation, etc.). The system includes a fluid reservoir and fluid conditioning system (heat exchanger and contamination control system). The operation of the system is either manual or automatic.

**DEVELOPMENT OF RDS SYSTEM**

The system is now in advanced stages of development. The RDS unit was designed to operate at 350 bar pressure and max. flow rate of 350 lpm. As hydraulic equipment manufacturers currently do not produce pump/motor units capable of meeting the requirements of the PDREM System, the RDS unit was developed over the last 18 months from scratch by the company developing the PDREM system.

Development of hydraulic pump/motor of this large size is a rather complicated matter and is to a large extent dependent on the access to the know-how. As such know-how is jealously guarded by the established hydraulic manufacturers and was not easily available, the development was necessarily based on steep learning-curve. The major issues in design of pumps/motors are:

- selection of materials for major tribological pairs (valve plate/cylinder block, slippers/swash plate, pistons/cylinder block).
- Hydrodynamic phenomena occurring at valve plate/cylinder block, pistons/cylinder block, slippers/swash plate interfaces.
- Dynamic interaction between various components of the unit, and the unit and vehicle system.

Figure 3 shows these and other factors and effects which were taken into consideration while designing the RDS unit (dynamic considerations). The current RDS unit is...
in operation for over 500 hours and was tested on full scale laboratory test rig and in vehicle field trials.

Modelling and Simulation
The simulation plays an important part in the development of such a system as cost of development is reduced. Three types of simulation/analytical studies are carried out on the system:

1. Simulation of steady-state and dynamic characteristics of the RDS unit, and complete system (RDS unit plus control system and vehicle dynamics), [12-13]. The simulation models were developed using Vissim modelling software, [14].

2. Simulation of fluid dynamic phenomena, for example at the interaction of valve plate/cylinder block and slipper/swash plate.

3. Simulation of RDS/vehicle during various drive cycles, [15]. The system was modelled using Advanced Vehicle Simulator Advisor 3.2, [16].

SIMULATION STUDIES (ADVISOR)
Advisor (ADvanced Vehicle SimulatOR) software, developed by US National Renewable Energy Laboratory, is a set of model, data, and script text files for use with Matlab and Simulink. It allows analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles and also provides a basis for the detailed simulation and analysis of user defined drivetrain components and verification of vehicle data. The models used are mostly empirical and quasi-static, using data collected in steady state (for example, constant torque and speed) tests and correcting them for transient effects such as the rotational inertia of drivetrain components. The software is used to estimate the fuel economy of unbuilt vehicles, to compare conventional and hybrid driveline energy gains and losses. Other information gained from Advisor include vehicle emissions produced on a number of cycles and capability to evaluate hybrid vehicle's engine control logic and optimise the system (e.g. the gear ratios). An interesting feature of the Advisor is the application of backward simulation approach in which starting from desired outputs the required inputs are computed. This is opposite procedure to the commonly used forward simulation approach which starts when command input is issued and then outputs are computed. The Advisor was used to model PDREMS installed in a heavy vehicle and, as it did not include models of the hydraulic hybrid drive, the mathematical model of the system was developed. The vehicle input screen is shown in Figure 4 and
the top level model of the Vehicle-PDREMS is shown in Figure 5.

TESTING

A prototype RDS system has been fitted to a Permo-Drive’s Freightliner FL112 and these trials were carried out to evaluate the system and to provide fuel savings data. In order to conduct testing in a controlled environment these tests were conducted at an airstrip, Figure 6. Tests simulating garbage truck cycle were run with the PDREMS system not activated, followed by test runs over the same course with the PDREM activated. Data for test vehicle are listed in Table 1. The vehicle was equipped with a Jacobs engine brake and a Permo Drive Regenerative Drive Shaft (PDREM System) capable of high levels of retardation (and propulsion). RDS was set to cut in at 500 rpm, and cut out in retard at 225 rpm. The vehicle had travelled less than 200,000 km at the time of the tests. Fuel tests were based on procedures in the SAE Recommended Practices SAE J1264 Oct. 86 and SAE J1321 Oct. 86, but with enhancements to facilitate start-stop drive cycle testing. The relative fuel effectiveness of the
RDS was determined as a percentage improvement factor.

<table>
<thead>
<tr>
<th>Test Vehicle</th>
<th>1998 Freightliner FL112 6X4</th>
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</thead>
<tbody>
<tr>
<td>Gross Weight:</td>
<td>17.24 tonnes</td>
</tr>
<tr>
<td>Prime Mover:</td>
<td>8.32 tonnes</td>
</tr>
<tr>
<td>Trailer:</td>
<td>8.92 tonnes</td>
</tr>
<tr>
<td>Load:</td>
<td>25.00 tonnes</td>
</tr>
<tr>
<td>Prime Mover &amp; PDREMS¹</td>
<td>10.38 tonnes</td>
</tr>
<tr>
<td>Transmission</td>
<td>18 speed overdrive Eaton Transmission</td>
</tr>
<tr>
<td>Engine</td>
<td>Caterpillar C12 430 HP @ 2100 rpm</td>
</tr>
<tr>
<td>Differential ratio</td>
<td>4.33:1</td>
</tr>
</tbody>
</table>

¹The "Proof of the concept" system used commercial components, the production PDREMS will be considerably lighter.

The fuel saving was calculated using the relative fuel usage of the same vehicle with and without the RDS being activated. Accuracy while employing these techniques and using the portable tank weighing method is considered, based on previous test experience, to be +/-1%. Fuel consumption data was collected over several test drive cycles which simulate urban start-stop driving. Two series of tests were run, one without PDREMS and the second with the PDREMS activated. The fuel saving when PDREMS was employed, averaged over all runs, was 37%, [17]. Acceleration/deceleration tests were also run on the airport strip. The test vehicle was the same which was used in the fuel tests. Four test runs were carried out, Table 2. Averaged data for acceleration and deceleration tests is plotted in Figures 7 and 8. We can observe a marked increase in both acceleration and deceleration performance of the vehicle when RDS unit is operating.

CONCLUSIONS

The paper presents some aspects of the development of the hydraulic hybrid drive for heavy vehicles. The system was designed and built to take advantage of high pressure fluid power technology. The preliminary simulations have shown the feasibility of the system and this was subsequently confirmed by field tests.

ACKNOWLEDGEMENTS

The authors acknowledge assistance of Permo-Drive Technologies Ltd staff in providing the data quoted in this paper. The fuel tests results were based on the report by Mr. Harry Close, Consulting Transport Engineer, available from website http://permo-drive.com.

REFERENCES

Figure 7 Acceleration tests

Figure 8 Deceleration tests

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