MODEL OF A HYDRAULIC HYBRID VEHICLE WITH REGENERATIVE SUSPENSIONS

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Abstract - This paper explains the basic principles of hydraulic hybrid vehicles. A brief overview of the most recently published papers in this area was made. The basic models of hydraulic hybrid vehicles are shown and explained: parallel, series and power-split hydraulic hybrid vehicle. A new series hydraulic hybrid vehicle model with a regenerative hydraulic suspension system is also presented. The idea is that the vibration energy of the vehicle is utilized through the regenerative hydraulic suspension for obtaining electric power for the drive of the auxiliary equipment of the vehicle. The regenerative hydraulic suspension system with all its basic elements is presented and explained in more detail for a better understanding of this energy harvesting system.

Index Terms - energy harvesting, hydraulic suspension, series hydraulic hybrid vehicle, sustainable energy

I. INTRODUCTION

Hybrid energy systems have become increasingly popular over the last few years. When it comes to hybrid vehicles (HV), the term hybrid means that two sources of power are used together to drive a vehicle. Hydraulic hybrid vehicle (HHV) usually uses hydraulic power to run the wheels while the other source (most commonly the internal combustion engine) drives the pump inside hydraulic system. This hydraulic hybrid technology is actively explored in the automotive industry to increase vehicle efficiency. Also, the advantage of HHV compared to conventional vehicles is the ability to store energy in a hydraulic accumulator. When the engine is idling, the energy produced by the engine is lost.

None of this energy is used to run the vehicle. HHV can continue to store this energy in the accumulator while the car is in idle state. When the hydraulic accumulator is pressurized, the internal combustion engine can be switched off and the stored energy can be used to restart the vehicle. Vehicles that use a classic brake disc can't use the energy that is lost by braking. The kinetic energy of the vehicle turns into heat energy and as such it loses in environment. These hybrid systems have the ability to store energy for later use through regenerative braking.

Implementing these systems on large trucks that often see stop and go action such as delivery trucks or sanitation trucks could greatly improve fuel economy and reduce brake wear. Recently, a large number of researchers have been involved in the subject of hydraulic hybrid systems. Ramdan et al.

[1] studied the optimal hydromechanical transmission configuration for a hydraulic hybrid city bus. This study simplifies the process of finding a suitable hydromechanical transmission configuration by utilizing the critical speed ratio. Soriano et al. [2] proposed and modelled a hydraulic hybrid power-train.

The proposed power-train models were executed using two different control algorithms, with and without predictive strategies, with data obtained from real routes. Wang et al. [3] studied energy management strategies for a power-split hydraulic hybrid wheel loader. An energy management strategy based on dynamic programming were developed to give full system optimization including both the drivetrain and the working functions. Bleazard et al. [4] developed a new sizing methodology to determine transmission sizing that meets both the efficiency and performance requirements for hydraulic hybrid. Honey et al. [5] presented an electro-hydraulic hybrid vehicle and compared it with a baseline battery electric vehicle under an urban driving cycle. The results show a reduction in the energy consumption as well as a reduction in the battery current transients. Chen et al. [6] described the configuration and working principle of HHV based on the hydraulic transformer (HT) to extend its energy-regenerated potential. The pressure pulsation characteristics between the HT and accumulator of the HHV were analyzed to optimize the system structure design. Our HHV model presented in this paper differs from the basic models by enabling energy harvesting using regenerative suspensions. For a better understanding of hydraulic hybrid operation, the basic models are briefly explained in the next chapter.

II. BASIC MODELS OF HHV

The basic models of HHV are parallel, series and

power-split. The parallel hydraulic hybrid vehicle (PHHV) features a classic conventional mechanical drive member. There is a direct connection between the engine shaft, the gearbox and the differential that gives the power to the wheels. The model of the PHHV is shown in Figure 1. The hydraulic pump/motor is connected to the shaft between the engine and the gearbox to allow the hydraulic accumulator to charge. Then connection between the hydraulic pump/motor with the internal combustion engine shaft is usually achieved by a belt or a gear transmission. The clutch located between the engine and the

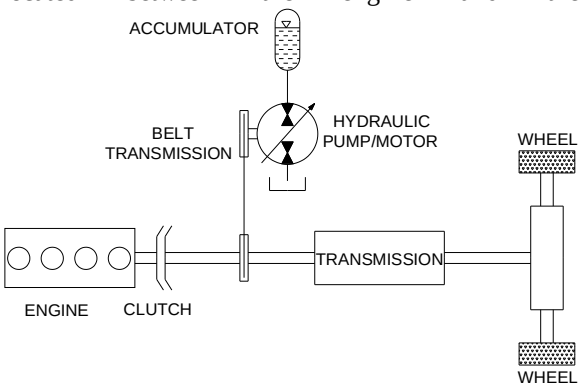


Fig. 1 Model of a parallel hydraulic hybrid vehicle (PHHV)

pump/motor serves to possibly isolate the engine from the road load. If the hydraulic accumulator has enough energy, the vehicle can only be driven by the hydraulics. This allows the engine to be switched off when there is no need for its operation and re-engaging when the energy in the accumulator drops to a low value. The disadvantage is that optimal engine performance is not possible since the engine speed depends on the speed of the wheel due to the transmission ratio. Unlike PHHV, there is no mechanical drive member in the series hydraulic hybrid vehicle (SHHV). The vehicle is powered by a hydraulic drive member. The hydraulic pump is directly connected to the engine shaft and allows the storage of energy in the hydraulic accumulator. Fluid flow from the hydraulic accumulator through the hydraulic motor generates the output moment. The model of the SHHV is shown in Figure 2. The hydraulic pump/motor is positioned in front of the differential, enabling the power to be transferred to the wheels. The clutch is again placed downstream of the engine to allow for decoupling of the engine and on/off engine management. This model of vehicle not only allows the engine output power to match load demand, but also the engine speed does not need to match the wheel speed due to the pump/motor at the wheels, allowing for optimal engine management. The power-split hydraulic hybrid vehicle (PSHHV) model combines the parallel and series models into one. The model of the PSHHV is shown in Figure 3. The mechanical drive train is similar to the PHHV design. Hydraulic pump/motor is also connected to the differential as in the SHHV design. This configuration allows for optimal

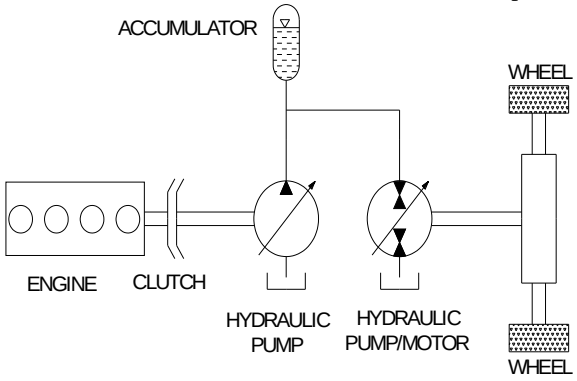


Fig. 2 Model of a series hydraulic hybrid vehicle (SHHV)

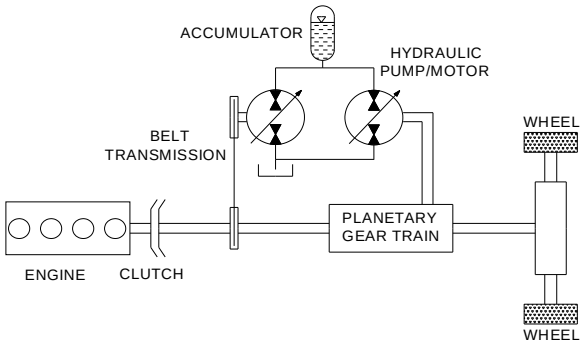


Fig. 3 Model of a power-split hydraulic hybrid vehicle (PSHHV)

engine management since, even if the engine is mechanically coupled to the drive wheels, the pump/motor at the wheels can be used to achieve desired wheel speed. This is possible because of the use of a planetary gearbox. The clutch between the gearbox and the engine allows the engine to be decoupled from the load, just like in the parallel and series models. The power-split model combines the advantages of both the parallel and series models. Mechanical drive train enables high efficiency power transfer from engine to wheels as in the parallel model while maintaining the optimum engine management as in the series model.

III. MODEL OF A HHV WITH REGENERATIVE SUSPENSIONS

For conventional vehicles, the electric batteries used by the auxiliary equipment are filled with an alternator attached to the engine shaft. For this reason, the fuel used in the vehicles is also partially consumed by rotation of the alternator for charging the battery. According to the source [7] this consumption is approximately 4% of the total fuel consumption in vehicles. The main idea of this paper is to make a more advanced model of HHV that can save the energy of the vehicle oscillation in hydraulic accumulator and reuse it to charge the electric battery/accumulator for auxiliary equipment. A more advanced model of SHHV with the regenerative suspension system is

shown in Figure 4.

For a better understanding of the operation of the vehicle, in Figure 4 there are four different color lines. Blue lines represent low pressure fluid pipes and tanks, red lines represent pipes and accumulators with high pressure fluid, double black lines represent a mechanical connection between components, while electrical components of the generator/battery are represented by a purple line.

Suppose it is a four-wheeled vehicle, although it should be emphasized that hydraulic hybrids are most often used for heavy vehicles, and such vehicles generally have 6 to 10 wheels. It is also important to point out that, if we have a larger number of wheels, it means a vehicle that has a larger mass. Mass plays a key role in the amount of energy that can be obtained by using regenerative suspensions. Generally speaking, if the mass of a vehicle is larger then there is a greater amount of energy that can be saved by using regenerative suspensions. The model in Figure 4

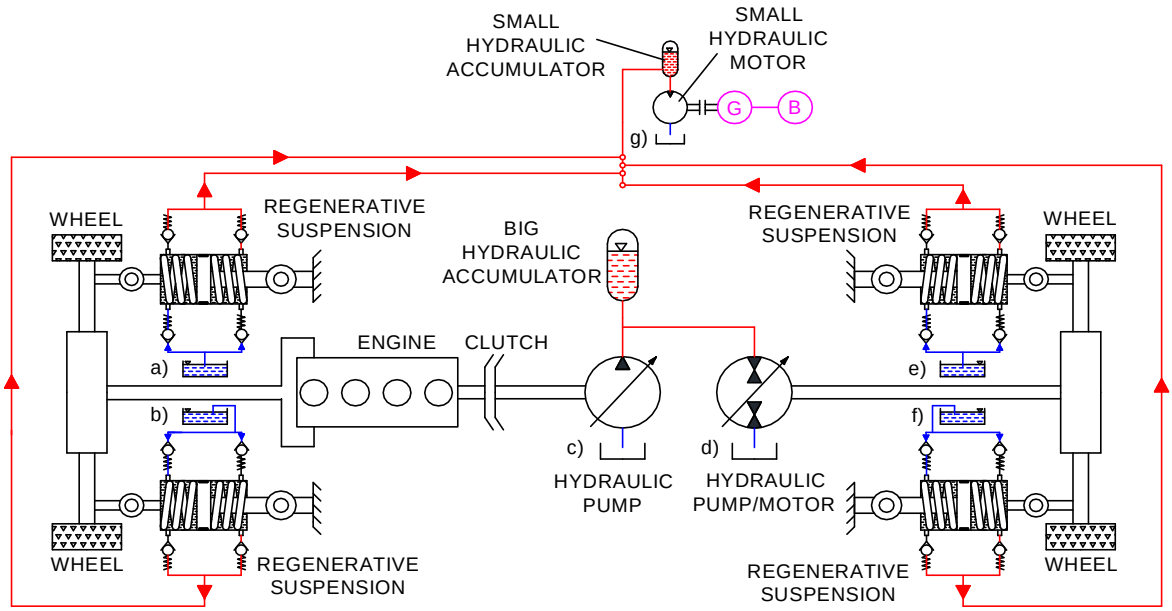


Fig. 4 Model of a HHV with regenerative suspensions

consists of an internal combustion engine that drives a hydraulic pump via a clutch. The pump presses the hydraulic fluid from the low-pressure tank (mark c) in Figure 4) to the hydraulic high-pressure accumulator (big hydraulic accumulator on the Figure 4) or to a hydraulic motor that gives rotation and torque at its output. All HHVs must have at least one high pressure tank and one low pressure tank. In Figure 4 marks a) to g) show a low-pressure tank. The division of the low-pressure container with the marks a) to g) is solely because of the visibility of the entire model. In reality all those small, individually marked low-pressure tanks represent a one large container from which the hydraulic fluid through the pipes goes to the executive elements (hydraulic cylinders, pumps and motors).

In order to increase the efficiency of the basic SHHV model, new parts of the system are introduced. There are four wheels in the Figure 4 that are connected to the chassis of the vehicle via four hydraulic regenerative suspensions. The basic function of the suspension in the vehicle is to provide a comfortable and safe ride regardless of road quality. In addition to this basic function, the regenerative hydraulic suspensions also have the function of saving energy in the hydraulic high-pressure accumulator (small hydraulic accumulator in Figure 4) that can be used to start the hydraulic motor (small hydraulic motor in Figure 4). By passing the pressure fluid through the small hydraulic motor, rotation is obtained on the output shaft and the used fluid in that process is returned to the low-pressure tank (mark g) in Figure 4). If the hydraulic motor output shaft is connected to the electric generator (symbol G in Figure 4) it is practically possible to get electricity in the electric battery (symbol B in Figure 4) that can be used to start the auxiliary equipment without any additional fuel consumption in the engine. This is precisely the reason why this HHV model with regenerative hydraulic suspensions is more efficient than the basic HHV models explained in Chapter II. For a better understanding of this regenerative suspension system, only one fourth of the model will be observed. The models in Figures 5 and 6 also include a hydraulic motor, an electric generator and an electric battery. There are two regimes of regenerative hydraulic suspension system depending on the direction of force acting. When a vehicle is encountered on the road uneven or on any obstacle over which the wheel must cross, then the force that appears on the wheel acts in the direction opposite to gravity. The state of the system for this direction of force is shown in Figure 5. The force caused by the impacts on the road affects the wheel and the shaft to which the wheel is connected. The shaft is mechanically coupled to the cylinder

housing and the force is transferred from the wheel to the regenerative suspension. The force causes relative displacement of the cylinder housing relative to the piston and the piston rod which are connected to the chassis of the vehicle. In cylinder chamber "A" there is an increase in working volume and there is a pressure drop causing the opening of the check valve 1. The cylinder chamber "A" is supplemented by fluid through the pipe from the low-pressure tank. In the cylinder chamber "B" there is an increase in working pressure and reduction of the working volume (compression). Increasing the pressure in chamber "B" causes the opening of the check valve 4 and the fluid fills the high-pressure accumulator. At the same time as the check valves 1 and 4 are open and the fluid

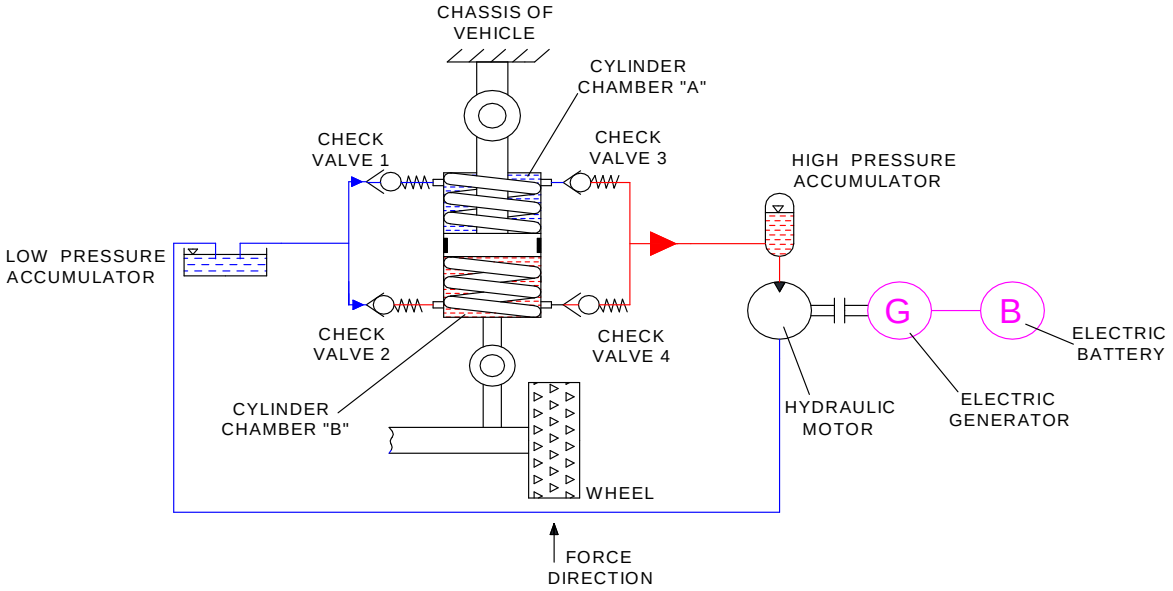


Fig. 5 The principle of hydraulic regenerative suspension – force direction opposite to gravity

flows, the high fluid pressure from the cylinder chamber "B" keeps the check valves 2 and 3 closed. Fluid flow from the high-pressure accumulator through the hydraulic motor causes rotation of the output shaft of a motor. The hydraulic motor causes the rotation of an electric generator that produces electricity that is stored in the electric battery. Energy obtained through this kind of way is free and renewable and can be used to power auxiliary vehicle equipment. In the second mode of operation, the vehicle can hit a hole in the road and then the mass of the wheels and all the parts that are connected to it will cause the force acting in the direction of the gravitational force. The state of the system for such a force direction is shown in Figure 6. The wheel mass and the parts connected to it cause the movement of the cylinder housing relative to the piston which is connected to the chassis of the vehicle. In cylinder chamber "B" pressure drop occurs and check valve 2 opens. Due to the increase in volume and

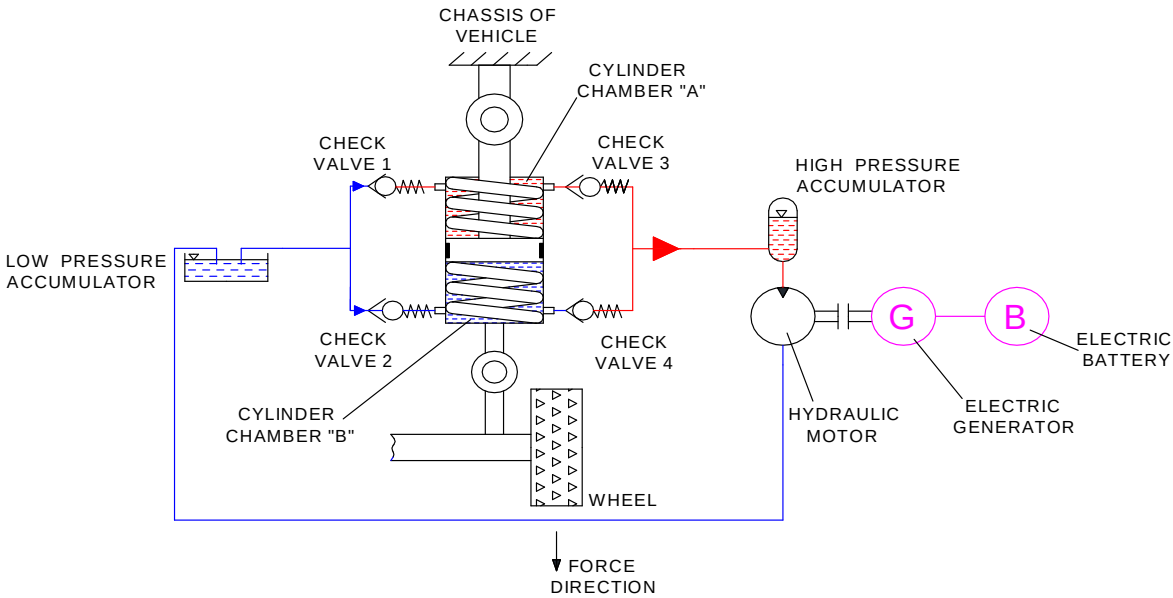


Fig. 6 The principle of hydraulic regenerative suspension – the direction of force is equal to the direction of gravity

pressure drop in chamber "B", the flow of hydraulic fluid from the low-pressure tank towards the chamber "B" occurs. In the cylinder chamber "A" there is an increase in working pressure and reduction of the working volume (compression). Increasing the pressure in chamber "A" causes the opening of the check valve 3 and the fluid fills the high-pressure accumulator. At the same time as the check valves 2 and 3 are open and the fluid flows, the high fluid pressure from the cylinder chamber "B" keeps the check valves 1 and 4 closed. The operating principle of the hydraulic motor and the process of obtaining electricity in the electric battery is the same as in the previous mode of operation.

During driving, these oscillations that are shown through these two modes of operation are constantly coming up. Vibrations occur most frequently when crossing the obstacle or holes on the road, during vehicle acceleration/deceleration or during vehicle turning in the road curve. The actual suspension system in the vehicle continually works alternately between these two modes of operation as explained and illustrated in Figures 5 and 6.

CONCLUSION AND FUTURE WORK

This article presents and explains the new SHHV model that uses regenerative hydraulic suspensions instead of conventional suspensions. The principle of regenerative hydraulic suspensions that can be used for such application is explained in detail. Obviously, such a system certainly has higher initial financial investment than a conventional vehicle, but it is important to point out that the energy obtained through these regenerative hydraulic suspensions is completely free and renewable. This reduces the amount of fuel consumed in the engine, which results in increased vehicle efficiency and reduced emissions of harmful gases. In the future, a plan is to develop mathematical model and a physical prototype of this regenerative hydraulic suspension system for the purpose of proving these theoretical ideas.

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