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Hydraulic Regenerative Braking System

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Abstract: ***In the current scenario of rising fuel prices and increased environmental awareness, it has become essentially necessary for the vehicles to have a better fuel saving technology. To overcome this, advancement in automobile technology has given rise to Hybrid vehicles which has a promising and cleaner future. At present, many electric and hydraulic hybrid vehicles are available but none of them have a strong advantage over the conventional vehicles because of their inherent inefficiencies. The aim of this project is to create an improvised model of hydraulic regenerative braking system. The system consists of a reversible hydraulic unit which would act both as a pump and motor based on the requirement. The hydraulic fluid is pumped to high pressure accumulator which converts mechanical energy to hydraulic energy and vice-versa during the phases of braking and acceleration, thereby recovering the energy wasted during braking. The main advantages are reduced power consumption and improved performance***

Keywords: Accumulator, Brakes, Efficiency, Hydraulic Hybrid

1. Introduction

Conventional braking systems uses friction to counteract the forward momentum of a moving car. Brake pads are placed around the wheels which are pressed against the wheel to reduce the speed of the vehicle, generating a lot of heat. About 30% of the car’s energy is wasted as this heat is dissipated into the atmosphere. Due to continuous usage, over a period of time the break wears out due to application of friction and heat and hence the braking efficiency decreases causing more energy to be required for braking. In a hybrid vehicle with regenerative braking, some part of this energy can be recovered and utilized by converting it into usable energy. All of the energy wasted cannot be recovered as some part of it is lost due to friction and other drains in the system but this system can improve the overall efficiency of the vehicle. [1]

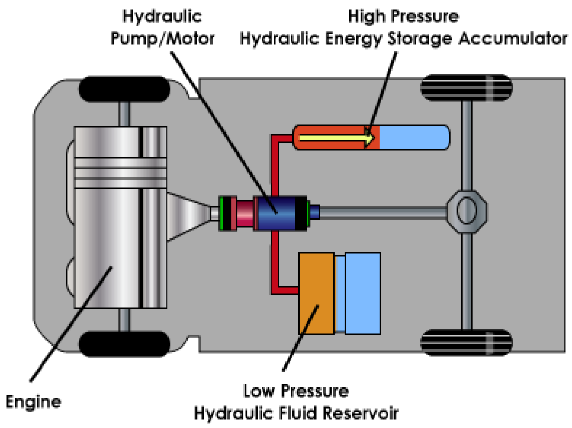
Gas/electric hybrid cars are popular, with many companies like Toyota or Honda offering hybrid models or versions of their models with hybrid drive trains. This type of vehicles uses both gasoline engines and electric motors powered by lithium ion batteries to move the car. These batteries get charged though a process called regenerative braking. The brakes in a car works in the following way: As the brake is applied, the fluid present in a cylinder gets compressed, hence hitting the brake pads with high pressure. This causes the pads to rub against the wheel which stops the wheel due to friction. A lot of heat is generated in this process, which is lost. When a gas/electric hybrid brakes, that friction is captured and used to charge the battery. The battery then powers the electric motor.

Hydraulic Hybrids uses three main components to power a vehicle at slow speeds and to augment the gasoline engine. Fluid is stored in a low-pressure reservoir. A pump moves the fluid from the reservoir to a high-pressure accumulator. The accumulator holds not only the fluid brought over by the pump, but also pressurized nitrogen gas.[2]

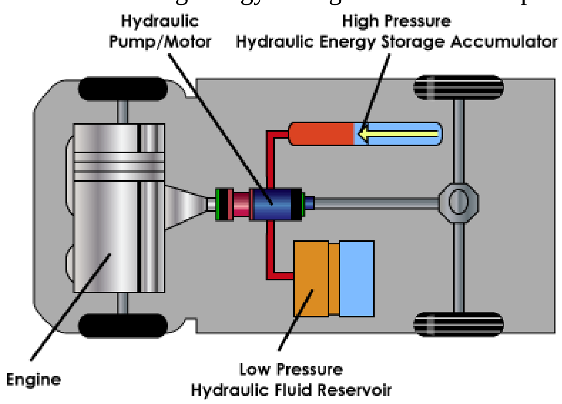
These three components work together, but to get things started, they need energy. Like gas/electric hybrids, that energy is gathered through regenerative braking. As the vehicle slows, the pump is activated, and moves fluid from the reservoir to the accumulator. As pressure in the accumulator builds, it acts like a fully charged battery in a gas/electric hybrid, ready to power the electric motor. Instead of sending power to the electric motor, which then sends it to the driveshaft (the part of the car which sets the wheels in motion); the accumulator sends its energy (in the form of nitrogen gas) directly to the driveshaft. As that happens, the vehicle accelerates, and the pump moves the fluid back to the reservoir, ready to charge the accumulator again.

Parallel hydraulic hybrids:

There are two ways those components can be coupled with a vehicle. The first, a parallel hydraulic hybrid, simply connects the hybrid components to a conventional transmission and driveshaft. While this allows the system to assist the gasoline engine in acceleration (when the gasoline engine is working its hardest), it doesn't allow the gasoline engine to shut off when the vehicle is not in motion. That means the vehicle is always burning gas (unlike gas/electric hybrids, which have engines that shut off at slow speeds or during a stop). This is the main disadvantage, when directly compared with the gas/electric hybrids, but in spite of this, the parallel hydraulic system does have significant benefits, including a 40 percent increase in fuel economy. The next figure demonstrates the high pressure accumulator storing energy during the brake process. [3]

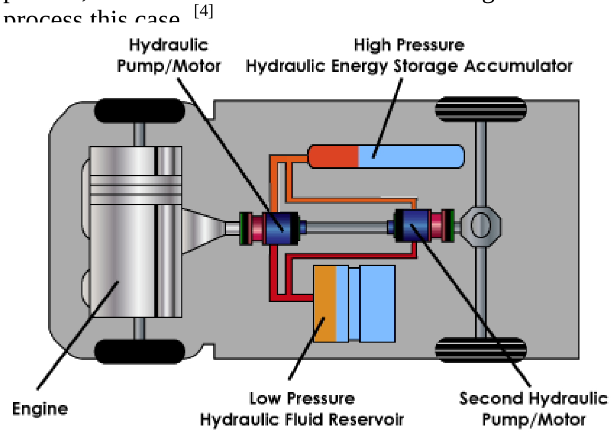


This figure demonstrates the inverse, the high pressure accumulator releasing energy during the acceleration process.



Series hydraulic hybrids:

Series hydraulic hybrid systems use the same process as parallel, but doesn't use a conventional transmission or driveshaft and transmits power directly to the wheels. Energy has to pass through a number of components before hitting its target to make it more efficient. Because the hydraulic system itself is turning wheels, not a regular transmission or a driveshaft, the vehicle's gasoline engine can be shut off, resulting in even more fuel savings. With the added efficiency and the ability to shut off the gasoline engine, series hydraulic hybrids are estimated to improve fuel economy by 60 to 70 percent, and lessen emissions. The next Figure demonstrates process this case.[4]



Problem definition

There are many losses and inefficiencies which arrive in an automobile which increase the fuel consumption per distance covered, thereby increasing the pollution. Hybrid vehicles are proving to have a promising and cleaner future. At present many electric and hydraulic hybrid vehicles are available but none have a strong advantage over the conventional vehicles because of its inherent inefficiencies. An energy efficient hydraulic regenerative braking system incorporated in a hydraulic hybrid has the potential of saving these lost energies and thereby improving the fuel efficiency of the vehicle.

Proposed solution

The proposed solution is to create a model of hydraulic regenerative braking system which would perform the following operations:

1) To stop the flywheel (perform the act of braking).
2) To store the energy of braking.
3) To return it back to the flywheel when required.

Here the flywheel acts as the kinetic energy storage device which is equivalent to a moving vehicle. Both the systems possesses inertia of motion and hence the results obtained by the model can be compared to a real life vehicle.

2. Components used in fabrication of model

1) Electric motor

An electric motor is an electrical machine that converts electrical energy into mechanical energy. The reverse of this would be the conversion of mechanical energy into electrical energy and is done by an electric generator. Electric motor used in the project is to provide energy to the flywheel. It is the prime mover of the system. It is similar to the engine in an automobile. Engine in an automobile provides the vehicle with linear kinetic energy whereas here in the project the rotational kinetic energy is provided by the electric motor.

2) Flywheel

A flywheel is a rotating mechanical device that is used to store rotational energy. Flywheels have a significant moment of inertia and thus resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. The kinetic energy of the flywheel is given by,

$$E = \frac{1}{2} I\omega^2$$

$$E = \frac{1}{2} mV^2$$

This kinetic energy of the flywheel can be related to the linear kinetic energy of the moving vehicle.

3) Gear pumps

Gear pumps (with external teeth) (fixed displacement) are simple and economical pumps which convert mechanical energy to hydraulic energy. Here in this project, it is required to convert the mechanical energy (provided due to the inertia of motion present in the rotating flywheel) to hydraulic pressure energy .the pump can be considered as a transducer i.e. convert one form of energy to the other. The kinetic energy is converted to pressure energy by pumping fluid from a low pressure state to high pressure state.

4) Hydraulic Accumulator

A hydraulic accumulator is a pressure storage reservoir in which a non-compressible hydraulic fluid is held under pressure by an external source. The external source can be a spring, a raised weight, or a compressed gas. Accumulator in this project is used to store high pressure hydraulic fluid coming from the hydraulic pump. The fluid is kept under high pressure by compressing N_2 gas in the other chamber. The high pressure fluid is returned back to the pump now acting as a motor when required.

5) Pressure Relief valve

The relief valve (RV) is a type of valve used to control or limit the pressure in a system or vessel which can build up for a process upset, instrument or equipment failure, or fire. In the project the pressure relief valve is set at 50 bar cracking pressure to maintain safe operation of the accumulator.

6) Directional control valve

Directional control valves are one of the most fundamental parts in hydraulic machinery as well and pneumatic machinery. They allow fluid flow into different paths from one or more sources. The movement of the spool restricts or permits the flow, thus it controls the fluid flow. With the combination of the check valves which allow only one way flow of the hydraulic fluid the requirement of the hydraulic circuitry is met. Thereby allowing the fluid to flow only in one direction in one operation.

7) Hydraulic Fluid

Hydraulic fluids, also called hydraulic liquids, are the medium by which power is transferred in hydraulic machinery. Common hydraulic fluids are based on waste, mineral oil or water.[5]

3. Fabrication, assembly and working of model

A. Fabrication of model

The model was designed in a modular approach. The following are the components of the model in the order of flow of energy:

1) Electric motor
2) Flywheel
3) Gear pump
4) Pressure relief valve
5) Directional control valve
6) Hydraulic accumulator

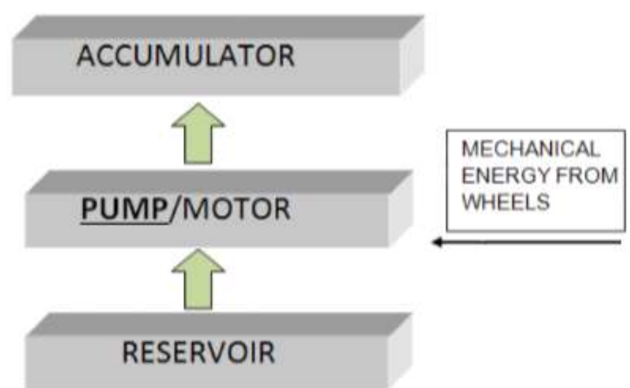
The structure was welded in two levels. They (levels) were created to have a compact arrangement of components and ease of engagement and disengagement of systems. The energy transfer between the mechanical components was to take place with the help of belt and pulley drives. In the upper level an electric motor, hydraulic pump/motor system and the control valves were placed. While in the lower level the flywheel, accumulator and the reservoir were placed. The flywheel was keyed to a shaft and the shaft was simply supported by two pillow blocks on either sides. The pillow blocks were further rested on transverse beams coming from the structure. The farther ends of the shaft were fixed with pulleys for transfer of energy through V belts. One end of the shaft of the flywheel having a pulley was fixed with the electric motor with the help of a V belt. This belt drive would transmit power from the electric motor to the flywheel. The other end of the shaft having a pulley was connected to an engagement- disengagement idler pulley arrangement, with the hydraulic pump motor system. The lever when pulled would lead to increase in belt tension and as a result the transmission of energy from the flywheel shaft would take place to the hydraulic pump/motor system. Hydraulic connections were made as per the hydraulic circuitry requirements and the valve block was positioned on the transverse bar for ease of operation. The hydraulic accumulator was firmly clamped to the vertical bar.

B. Working of model

The system developed would work in two different modes:

1) Braking mode(stopping)

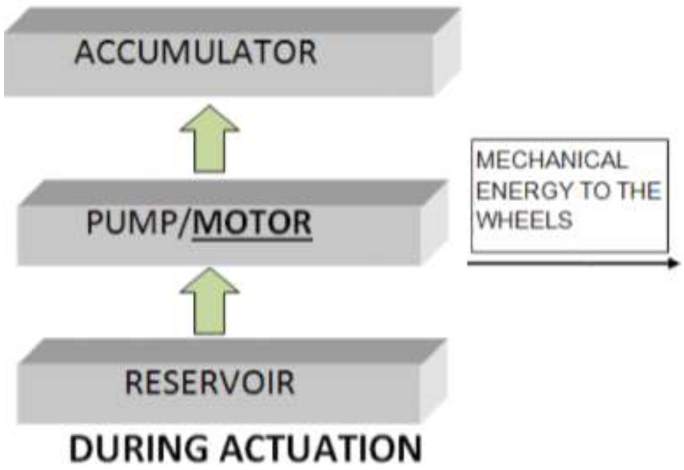
In this mode the kinetic energy is converted to pressure energy. Here in this project kinetic energy is fed by the rotating flywheel; the pump takes this energy and converts it to pressure energy. For braking to take place there must be kinetic energy in the flywheel and this energy is provided by the electric motor. The electric motor rotates the flywheel and thereby storing energy in it. When the brake lever (engagement lever) is engaged the energy is transferred from the flywheel to the hydraulic pump/ motor system. This system effectively converts the input mechanical energy to hydraulic energy. The hydraulic fluid flows through the circuitry and is stored at high pressure in an accumulator for further use.



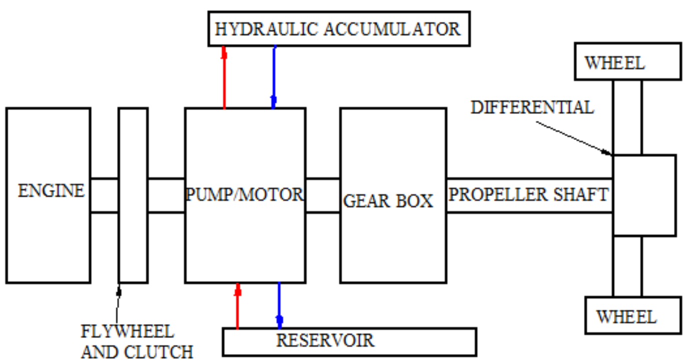
DURING BRAKING

2) Acceleration mode

In this mode the pressure energy is converted back to kinetic energy. The reverse process of the braking mode takes place. When acceleration is needed the stored pressure energy is reversed back with the help of direction control valve. The fluid turns the pump/motor system (gear pump) and thereby rotating the flywheel backwards. The figure below depicts the working in actuation mode.



The complete circuitry of the system is depicted below:



4. Design Analysis the Model

1) Design of electric motor and flywheel

Measurements of the flywheel,

a) Mass, m = 20 Kg
b) Radius, r = 190×10^{-3} m
c) Thickness, t = 15×10^{-3} m
d) Mass moment of inertia of flywheel, I =mk²=0.36 Kgm²

Rotational kinetic energy of the flywheel is given by the formula, $K.E_{Rotational} = 1/2\ I\ \omega^2$

Energy of flywheel when the flywheel is rotating at 1400 rpm(146 rad/sec), $K.E_{Rotationsl} = 1/2\ I\ \omega^2 = 3847.53$ J

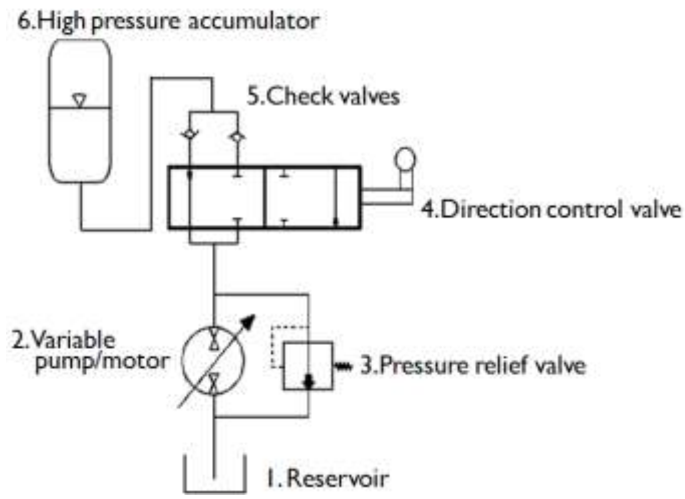
Power of electrical motor required to rotate the flywheel, P = E/t in 5 sec = P = (3847.53 J) / 5 = 769.4 W

Therefore, a 1 HP motor was chosen to rotate the flywheel to the required speed of 1400rpm.

The flywheel was coupled to the electric motor with the help of a belt drive of 1:1 drive ratio so as the flywheel and the motor both run at 1440 rpm.

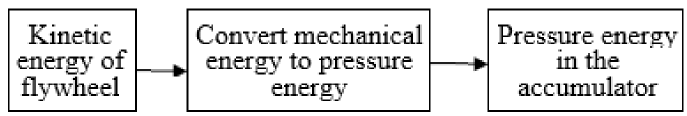
2) Hydraulic Circuit Design

The hydraulic circuitry is so designed that it operates in 2 positions, one is braking and the other is acceleration. The suction port of the hydraulic pump is connected to the reservoir while the delivery port to the dc vale block. The DC valve is a hand operated valve. Check valves are connected in opposite directions to ports A and B of the valve. The connection is completed by connecting with a "T" joint with the accumulator. The hydraulic circuit is as shown below.



3) Design of Accumulator

For the design of accumulator law of conservation of energy was used.



Change in Kinetic energy = work done inside the accumulator

$\frac{1}{2} I\omega^2 = -\int_{v_1}^{v_2} P dv$ (negative since $v_2 < v_1$)

$P_1 v_1^n = P_2 v_2^n = P v^n$

$P = \frac{P_1 v_1^n}{v^n}$

$\frac{1}{2} I\omega^2 = -\int_{v_1}^{v_2} \frac{P_1 v_1^n}{v^n} dv$

$\frac{1}{2} I\omega^2 = -P_1 v_1^n \int_{v_1}^{v_2} \frac{1}{v^n} dv$

$\frac{1}{2} I\omega^2 = -P_1 v_1^n \{\frac{1}{(1-n)v^{n-1}}\}_{v_1}^{v_2}$

$\frac{1}{2} I\omega^2 = -\frac{P_1 v_1^n}{(1-n)} \{\frac{1}{v_2{}^{n-1}} - \frac{1}{v_1{}^{n-1}}\}$

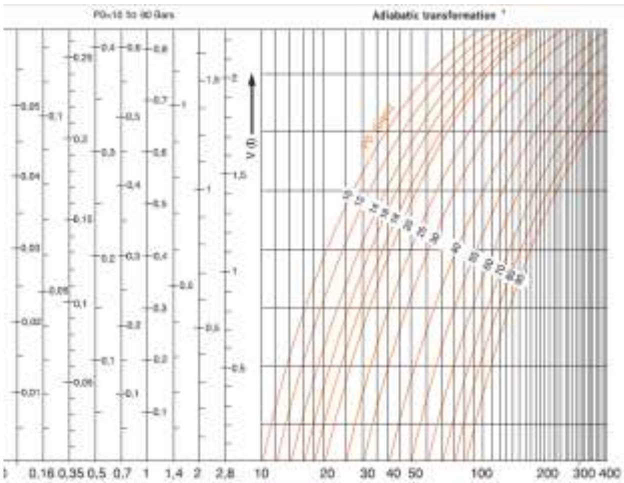
$\frac{\frac{1}{2} I\omega^2 (n-1)}{P_1 v_1^n} = \{\frac{1}{v_2{}^{n-1}} - \frac{1}{v_1{}^{n-1}}\}$

$\frac{\frac{1}{2} I\omega^2 (n-1)}{P_1 v_1^n} + \frac{1}{v_1{}^{n-1}} = \{\frac{1}{v_2{}^{n-1}}\}$

$v2 = [\frac{1}{\{\frac{\frac{1}{2} I\omega^2 (n-1)}{P_1 v_1^n} + \frac{1}{v_1{}^{n-1}}\}}]^{\frac{1}{n-1}}$

Choosing v_1 and P_1 based on the requirement of braking and the pressure vs volume charts therefore choosing 1.4 litre accumulator and initial charge pressure of 20 bars. Therefore on substitution of the above values in the above equation gave the following value

$v_2 = 468 \times 10^{-6}\ m^3$



Volume of fluid in the accumulator is complimentary to the gas volume of the accumulator i.e. sum of gas volume and hydraulic fluid is equal to the nominal volume.

$vf2 = vn - v_2$

$vf2 = 1.4 = 10^{-3} - 468 \times 10^{-6}$

$vf2 = 932 \times 10^{-3}\ m^3$

We have the amount of fluid required to be pumped into the accumulator to convert the entire kinetic energy to pressure energy which will be required to design the pump further on.

4) Design of Hydraulic Pump

Flow accumulated in the accumulator must be provided by the hydraulic pump.

$vf2=\int_0^t Q\,dt$

$vf2=\int_0^t V_G n_s\,dt$

$vf2=\int_0^t V_G \frac{\omega v}{2\pi}dt$

$vf2=\int_0^t V_G \frac{(\omega u-\alpha t)}{2\pi}dt$

$vf2=\frac{V_G}{2\pi}\int_0^t(\omega u - \alpha t)\,dt$

$vf2=\frac{V_G}{2\pi}\{\omega ut - 0.5\alpha t_{2}\}0t$

$vf2=\frac{V_G}{2\pi}\theta$, Where θ is the angle covered by the flywheel

On substituting the value of vf2, the angular velocity and design requirement time say 5 sec in the above equation to find the value of VG we get

$VG = 16 \times 10^{-6}\ m^3$ (cc)

Therefore a 16 cc pump was selected.

5) Test Conducted

A test was conducted on the model of HRB. The steps followed in conducting the test is as follows:

- The electric motor was switched on and allowed the flywheel to attain a steady speed.
- The electric motor was switched off, the flywheel is rotating because of inertia recorded the speed of the flywheel.
- Engagement lever was pulled and valve DC position to A
- Recorded the time taken to stop the flywheel
- To recover the energy back to the flywheel, Engagement lever was pulled and valve DC position to B
- Record the speed of the flywheel.

The following data was obtained:

Sl. no	Speed (when run by the electric motor) (rpm)	Time required for stopping (s)	Speed (when run by the hydraulic motor) (rpm)
1	1401	6.7	989
2	1398	6.6	979
3	1399	6.7	980

5. Conclusion and Future Scope

- The testing proves beyond a doubt that the system does regenerate energy usually lost during braking, which accomplishes the set goal of efficiency greater than 0% i.e. obtained value is 49.61%
- It is seen that greater the mass of the vehicle greater is the energy lost during braking and therefore greater is the capacity of it being regenerated.
- This system finds application in heavy vehicles which have very frequent stop go cycles like the city transport and refuse trucks.
- A car of mass 1000 kg and moving with a velocity of 40kmph (11.11 m/s) can harness energy up to 30.85 KJ with the given efficiency i.e. It can be used to accelerate the vehicle up to a speed of 28.26kmph (7.85m/s)
- This regeneration of energy will surely save the fuel which would have been required to accelerate the vehicle to given speed thereby, improving the fuel economy and reduced emissions.
- The mass of the system is lowest possible with the use of components available in market which would help reduce the fuel consumption in an actual vehicle.

6. Acknowledgment

We thank our college for providing us a golden opportunity to present our idea. Also, we would like to thank Dr. Satish, Mechanical Dept for being instrumental in developing our idea. Also, we take this opportunity to thank Chandru Sir for constantly guiding us in the right path.

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