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# Hydraulic Regenerative System for Bicycle

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## ABSTRACT

**This paper investigates the hydraulic regenerative braking system for a bicycle. The purpose of implementing this system is to lower the human effort required for driving a bicycle. The regenerative braking system can capture and reuse the energy that is normally lost due to braking. This paper represents a model of novel configuration for hydraulic regenerative braking system based upon the Matlab Simulink Environment. The influence of the key component parameters on the performance, braking and rate of energy recovery is analyzed. The simulation result helps in selecting proper components which will suit the proposed system most appropriately. Though the overall cost of the system is high the amount of human effort saved makes it worth of being implemented in real life.**

*Keywords* **-** bicycle, energy recovery, hydraulic hybrid, regenerative braking, Simulink

## 1. INTRODUCTION

According to the Environmental Protection Agency (EPA), an agency of the U.S. government, a report has been made in 2006 on Clean Automotive Technology Program [1], transportation is responsible for 30% of national $CO_2$ emissions. As a fuel- and- emission-free option to traditional modes of travel, bicycling remains an important means of transportation in cities and high-traffic areas. They are reliable, convenient, and sometimes faster than driving. However, because they require more work to operate, they are frequently dismissed for a car. In order to increase attraction to bicycles, a modification can be done to the bicycle which will consume less amount of human effort. A hydraulic regenerative system can be added to the conventional bicycle which can store the wasted energy, generally lost during braking and reuse it during accelerating the bicycle.

In a conventional bicycle system, during braking the kinetic energy is lost to the environment in the form of heat. This happens every time when we stop the bicycle. During acceleration we again have to invest energy to overcome the inertia of the bicycle and rider, thus requiring more effort to drive. In the mid of a city, where we require frequent stopping, the energy lost is considerable.

In hydraulic hybrid bicycle, instead of chain drive a hydraulic circuit is used to drive the rear wheel of the bicycle. During normal cycling mode human power is given as an input to the hydraulic pump. Then pump pressurizes the fluid and sends it to the hydraulic motor which is connected to the rear wheel of bicycle. During braking the motor acts as a pump for a short time and consumes bike momentum to pump the fluid. This pressurized fluid is stored into the accumulator which can be used as input to the motor during accelerating mode. This arrangement is also called as series hydraulic hybrid system.

This system is currently used in heavy vehicles such as dump trucks and busses, the efficiencies of the system have been measured experimentally and analytically. [9] the results indicate that the average efficiency of energy recovery of the system was 66%. The overall regeneration efficiency of the proposed hydraulic system (consists of three 2.5 litter accumulators, a Vickers fixed displacement 4.11 cm3/rev, an axial piston pump/ motor, and two 0.847 kg.m2 moment of inertia flywheels) is 73% [10]. Generally overall efficiency of the hydraulic system varies from 32% to 66% [4]. Although the result variation is high, yet it indicates that hydraulic regenerative braking system possesses a high potential of energy recovery [5].

In this paper a new configuration of hydraulic hybrid system is established. The model consists of a hydraulic gear pump, gear motor, accumulator, and a reservoir. These components are connected with hose and solenoid actuated valves. This model is also simulated with the help of Matlab Simulink environment. Based on simulation, the regenerative braking process will be investigated with regarded to the effects of main component parameters. The rate of recovery energy during regenerative braking is calculated.

## 2. ANALYSIS OF HYDRAULIC REGENERATIVE BRAKING SYSTEM

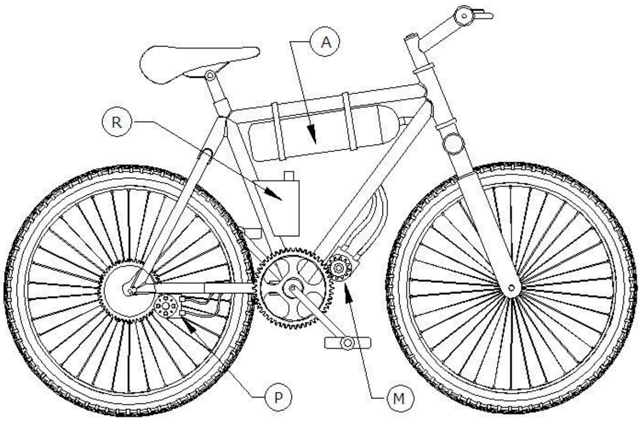


Fig. 1. Actual Model of bicycle

Above figure shows the arrangement of the main component on the bicycle frame. A reservoir (R) is connected to the vertical member of frame. Pump (P) is connected to the sprocket with the help of gear arrangement. Accumulator can be connected to the horizontal member of frame and hydraulic motor (M) is connected to the rear wheel with the help of gear arrangement. Valve arrangement and the electronic control system are not shown in the figure for sake of simplicity.

The hydraulic system consists of many components like pump, valves, motor, accumulators etc. Different functions of the regenerative system can be controlled by electrical system [8] since all valves are solenoid actuated. The function of the key component and the method to determine specification and working circumstances of the system are described below.

### 2.1 System Description

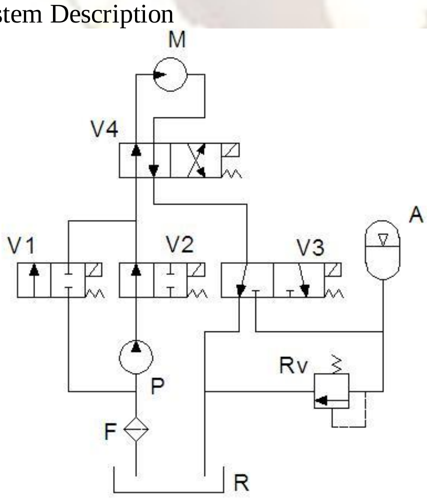


Fig. 2. Hydraulic Circuit of Regenerative Braking System

The hydraulic circuit consists of components like Hydraulic reservoir (R) to store the sufficient amount of hydraulic liquid, a hydraulic fluid filter (F) to prevent small metal or dust particles to enter into the system. Hydraulic Gear pump (P) which will pressurize the fluid and send it to the hydraulic motor during peddling. Valves (V1, V2, V3, and V4) are used accommodate different modes of riding like peddling, no peddling, braking, launching. A hydraulic gear pump motor (M) is used to drive the rear wheel during peddling and launching, while during braking it will convert mechanical energy into hydraulic energy. An accumulator (A) is used to store the hydraulic energy and release it during launching process. A pressure relief valve (Rv) used as a safety device. During braking, if accumulator is filled to its capacity then excess quantity of pressurized fluid will pass through pressure relief valve and flow into the sink [7]. The valves V1 and V2 are the 2×2 valve (on-off valve), Valve V3 is 3×2 valve (3 way 2 positions), and valve V4 is 4×2 valve (4 way 2 positions). All the valves are DC current actuated solenoid valves since manual operation of valves during cycling is not possible. The hydraulic pump and motor used are gear motors since they are fairly accurate, efficient and cheaper, also the hydraulic gear motor can also be used as a pump since the construction of both pump and motor is same. Accumulator used is bladder type since this type of accumulator is most suitable for mobile application than spring loaded or dead weight type. Also these accumulators can be pre-charged according to the application requirement [3]. The pressure relief valve is pilot actuated thus providing an automatic actuation. All the components are connected with the help of flexible hose.

### 2.2 Working of System

Complete ride of a bicycle can be classified in 4 basic modes like peddling mode, no peddling or cruising mode, braking mode and launching mode. In peddling mode the power provided by a human is directly utilized in propelling the bicycle. In cruising mode bicycle maintains its motion due to inertia. In case of braking mode, momentum of the bicycle is used to drive the pump which in turn fills the accumulator, and in case of launching mode the energy stored in the accumulator is used to propel the bike to gain the momentum without human effort. These different modes can be achieved with the help of actuation of different valves in the hydraulic circuit. The following diagram shows symbol of hydraulic direction control valve, the left block is considered as I position and right block is considered as II position. To activate the different modes during riding the valve position is shown in following table.

Table 1. Valve Actuation for different modes

| Mode | V1 | V2 | V3 | V4 |
|---|---|---|---|---|
| Peddling mode | I | II | I | I |
| Cruising Mode | II | I | I | I |
| Braking mode | II | I | I | II |
| Launching Mode | II | I | II | II |

In peddling mode the power provided by the rider is directly given to the hydraulic gear pump (P). This can be achieved by directly coupling the pump to the peddling sprocket through gear or chain or belt arrangement. The gear ratio of transmission depends upon the running conditions of pump. The Pump (P) sucks the oil from the oil reservoir (R) and sends it to the motor (M) through valve V2 and V4. The hydraulic motor is directly coupled to the rear wheel of the bicycle. The high pressure fluid runs the hydraulic motor and thereby propels the bicycle. This is similar to the hydraulic coupling. Low pressure oil coming out of the motor is sent back to the reservoir (R) through valve V4 and V3.

In no peddling situation the bike maintains its motion without peddling due to inertia of vehicle and rider or in case of going down the road. In this mode the pump (P) is bypassed from the hydraulic circuit. The motor (M) sucks the oil from the reservoir (R) through the valve V1 and V4 and sends it to the reservoir again through V4 and V3. The path selected is minimum resistance path and hence minimum amount of energy will be lost during this process.

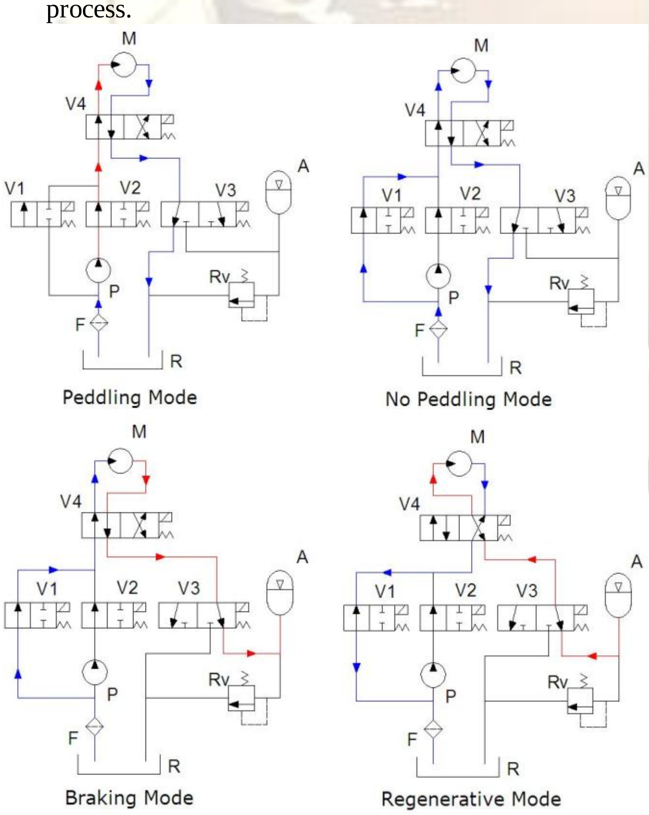


Fig 3. Working of Hydraulic system

During braking process, the pump (P) is isolated because peddling is not required during braking process. The low pressure oil from the reservoir (R) is sucked by the motor (M) through valve V1 and V4 and pressurized oil coming out of the motor is sent to the accumulator (A) through valve V4 and V3. During braking process the hydraulic motor (M) momentarily acts as a pump. The energy required to drive the motor is taken from the bicycle's kinetic energy and thus slowing down the bicycle. During braking process the accumulator (A) gets filled up by high pressure hydraulic oil. After complete filling of accumulator the excess oil is drained to the reservoir (R) through pressure relief valve (Rv).

During launching mode, the pressurized oil from the accumulator (A) is given to the hydraulic motor (M) through valve V3 and V4. This causes the hydraulic motor (M) to run and propel the bicycle. Energy stored in the accumulator is converted into kinetic energy. The low pressure oil coming from the Hydraulic motor (M) is sent back to the reservoir (R) through valve V4 and V1 respectively.

The procedure to select the component is shown below.

### 2.3 Component Specification Determination

The specifications of components in the proposed system were considered to reflect the characteristic of the average mountain bicycle with 26" wheel.

The energy required E to fully stop a bicycle from an initial velocity of $v_0$ is given by,

$$E = \frac{1}{2} m v_0^2 \qquad (1)$$

Where, $m$ is the total mass of bicycle and rider. $v_0$ is the longitudinal velocity at which brakes are applied.

Since the braking time is normally short and the braking torque is very large in comparison with the air drag and rolling resistance, these resistances are neglected. In such case the braking torque is given by,

$$T_b = \left(2 I_w + m R_w^2\right) \frac{a}{R_w} \qquad (2)$$

In this case, $I_w$ is mass moment of inertia of the wheel, $m$ is total mass, $R_w$ is the radius of the wheel and $a$ is the deceleration by which the vehicle is stopping.

Since it is a moving system the accumulator used is bladder type. Construction is similar to the pressure vessel except it is equipped with elastomeric bladder. Bladder separates the accumulator into two parts one of which is pre-charged nitrogen gas and other is hydraulic fluid [3].

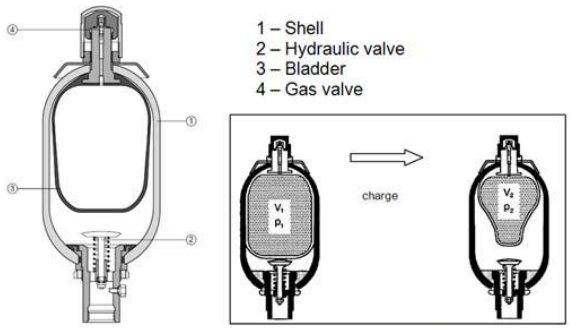


Fig. 4. Bladder type Accumulator

We consider nitrogen as an ideal gas and neglect the compression of hydraulic fluid. The relation between pressure and volume of gas can be given by following thermodynamic law.

$$p_i V_i^{\,n} = p\,V^n = p\,(V_i - V_f)^n = C \qquad (3)$$

Where $p_i V_i$ are the initial pressure and volume of gas and $p\,V$ are the final pressure and volume of gas respectively. $V_f$ is the volume of fluid in the accumulator and $C$ is the constant depending on the initial condition of the accumulator. $n$ is a ploy-index for an adiabatic process $n = 1.4$

Assuming that when braking process is done the pressure of hydraulic fluid inside the accumulator is $p_1$. Then energy that accumulator will store during braking can be given as,

$$E_{acc} = p_1\,V_f \qquad (4)$$

$V_f$ is the total volume of fluid flown into the accumulator during braking.

Size of accumulator is an important factor to ensure that the system could recover the kinetic energy of a bicycle at specific speed as much as possible. Also pressure at inlet of accumulator should not exceed maximum working pressure. If at any point the pressure at inlet becomes more than maximum working pressure of the system then fluid will bleed off reservoir resulting into loss of energy. The hydraulic accumulator should have enough space and flow rate to meet the system requirements.

From the equation (1) and (4)

$$V_f = \frac{m\,v_0^{\,2}}{2\,p_3} \qquad (5)$$

The capacity of the accumulator is established from the following equation.

$$p_0 V_0^{\,n} = p_1 V_1^{\,n} = p_2 V_2^{\,n}$$

Rearranging the above equation we can write,

$$V_A = \frac{V_f}{\left(\frac{p_0}{p_1}\right)^{1/1.4} - \left(\frac{p_0}{p_2}\right)^{1/1.4}} \qquad (6)$$

Where, $p_1$ and $p_2$ are the lowest and highest working pressures of accumulator during braking process. Here the charging and discharging process of accumulator is considered as an Adiabatic process. During braking process, motor (M) will momentarily act as pump. Torque required to operate motor is given by,

$$T_{4_p} = \frac{\Delta p\,.d}{\eta_T} \qquad (7)$$

Here, $\Delta p$ is the differential pressure across the motor (M), $d$ is the displacement of the motor (M) and $\eta_T$ is the torque efficiency of the pump.

Since the hydraulic system in bicycle need not to be sophisticated hence we use the simplest form of fixed displacement gear motor for the building of Hydraulic Circuit. Pressure differential across motor (M) during braking is given by,

$$\Delta p = p_1 - p_2 + \frac{f L \rho Q^2}{2 d_0 A^2} \qquad (8)$$

Where, $p_2$ is the pressure at inlet of the reservoir which can be considered as the atmospheric pressure. $f$ is friction coefficient of the fluid. $L$ is an effective hose length between reservoir (R) and accumulator (A). $\rho$ is oil density and $A$ is internal cross-section of the hose.

Pressure at the inlet of gas charged accumulator (A) during braking is given by,

$$p_1 = p_0 \left\{\frac{V_A}{V_A - \int Q_a\,dt}\right\}^{1.4} \qquad (9)$$

Where, $Q_a$ is the actual volumetric flow rate generated by the motor (M) during braking process. The actual volumetric flow rate of oil through motor (M) is given by,

$$Q_a = d\,.\,\omega\,.\,\eta_v \qquad (10)$$

Here $\eta_v$ is the volumetric efficiency of the motor and $d$ is displacement of motor.

During regenerative launching mode, the energy stored in the accumulator (A) is used to run the motor (M) and during this process the hydraulic energy will be converted into the mechanical energy.

Actual driving torque that motor (M) will generate is given by,

$$T_{4_m} = d\,.\,\Delta p\,.\,\eta_t \qquad (11)$$

In this equation, $\Delta p$ is the differential pressure across the motor (M), $d$ is the displacement of the motor and $\eta_T$ is the torque efficiency of the pump.

The differential pressure across the motor is calculated in the same way as mentioned above. The pressure at the inlet of the motor is given by,

$$p_1 = p_0 \left\{\frac{V_A}{V_A - \int Q_a \cdot \eta_v dt}\right\}^{1.4} \qquad (12)$$

Where, $\eta_v$ is the volumetric efficiency of the motor and actual fluid flow rate through the motor is given by,

$$Q_a = \frac{d \cdot \omega}{\eta_v} \qquad (13)$$

The actual rate of energy recovery of hydraulic regenerative braking system is defined as the ratio of energy stored in the accumulator and the kinetic energy of the bicycle.

$$\varepsilon = \frac{\sum_{i=0}^{\Delta t} p_i Q_{a_i} \Delta t_i}{\frac{1}{2} m \left(v_o^2 - v_{\Delta t}^2\right)} \qquad (14)$$

In above equation $\Delta t$ is the braking period.

$E_a = \sum_{i=0}^{\Delta t} p_i Q_{a_i} \Delta t_i$ is the regenerative braking energy

$E_b = \frac{1}{2} m \left(v_o^2 - v_{\Delta t}^2\right)$ is the kinetic energy of the bicycle corresponding to speed reduction from $v_o$ to $v_{\Delta t}$

## 3. Simulation

In order to investigate the performance of the system during braking as well as to verify the rate of energy recuperation of the system under a typical driving cycle, a hydraulic regenerative braking model is established. The model is implemented in the Simulink using fundamental blocks of Matlab Simulink. This system can be shown in following Fig. 5. In this model kinetic energy is given as input to the model after applying various mathematical transformations, effect of various parameters on the performance of the system is determined.

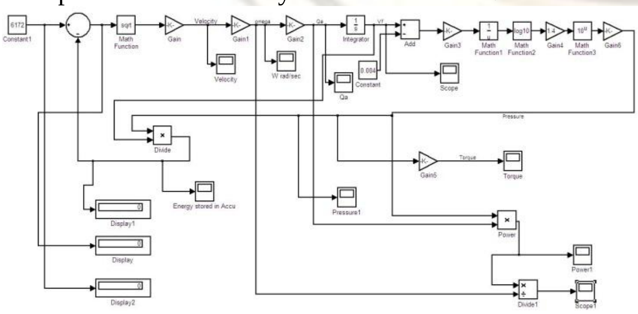

Fig. 5. Matlab Simulink model of HRB system

There are some assumptions made to build the model. For example, volumetric efficiency of the pump and motor, which is specified at nominal pressure, angular velocity and fluid viscosity, is considered as constant. The charging and discharging processes of accumulator are adiabatic. Resistances offered to the motion are neglected such as frictional resistance and aerodynamic resistance.

In the first part of simulation we consider effect of different pump on the performance of the bicycle. During this investigation other parameters of the system are kept constant. Here we consider 5 different pumps from different manufacturers and capacity as listed below [11][12][13][14]:

Table 2. Different pump that can be used on the system

| Pump | Displacement (cc/rev) | Min. Speed (rpm) | Max. Pressure (bar) |
|---|---|---|---|
| Bosch Rexroth AG AZPF-11 | 11.3 | 500 | 280 |
| Eaton Char-Lynn J series 129 | 8.2 | 750 | 140 |
| Bosch Rexroth AG AZPB-22 | 6.3 | 750 | 250 |
| Casappa Formula FP PL 10.5 | 5.34 | 650 | 280 |
| Roquet Pump Type LO | 3.3 | 750 | 240 |

Simulation is done considering the following conditions: the longitudinal velocity of the bicycle is 40 km/hr. The total weight of bicycle and adult rider is 100 kg. Gear ratio is 3. The accumulator used is bladder type accumulator with 4 liter capacity and charging pressure of 72 bar.

During the simulation, it is considered that the volumetric efficiency of the pump is 95% this is possible since pump will operate at low pressure and low rpm. The Fig. 6 shows the effect of pump displacement on the braking torque. The higher displacement pump will offer high resisting torque since it requires more power to operate. Due to this, deceleration will be higher and time required to stop the bicycle will be lesser. On contradictory the pump with lower displacement will offer less torque and hence lower deceleration with larger time to stop the bicycle.

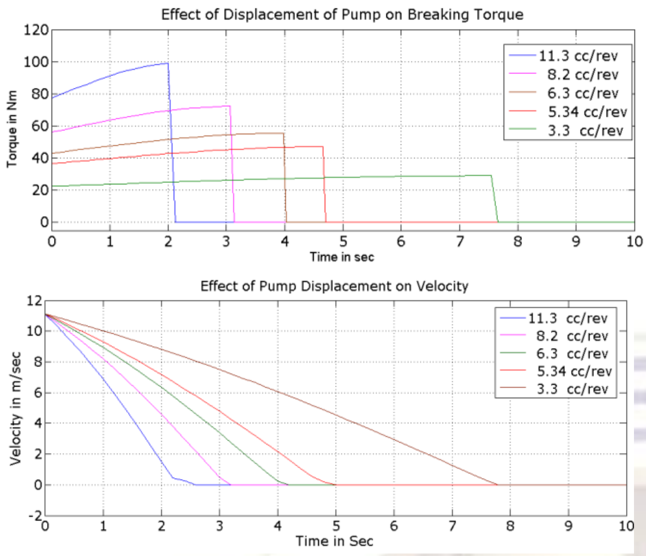


Fig. 6. Effect of different parameter on HRB system

The result of the above simulation for pre-charging pressure of 72 bar is be described as below,

Table 3. Result of different pump on the performance

| Pump | Max. Torque (Nm) | Braking time (sec) | Deceleration ($m/s^2$) |
|---|---|---|---|
| Bosch Rexroth AG AZPF-11 | 99.8 | 2.5 | 4.44 |
| Eaton Char-Lynn J series 129 | 73.4 | 3.1 | 3.58 |
| Bosch Rexroth AG AZPB-22 | 56.7 | 4.2 | 2.64 |
| Casappa Formula FP PL 10.5 | 48.3 | 5 | 2.22 |
| Roquet Pump | 29.7 | 7.8 | 1.42 |

From the above table we can see that Eaton Char-Lynn J 129 motor with displacement of 8.2 cc/rev show considerable results. Hence for finding out the effect of pre-charging pressure of accumulator on the performance of bicycle, we will consider the above pump. In this part of simulation all the parameters of the system are kept constant and the pre-charging pressure of accumulator is varied. The effect of pre-charging pressure on the torque and stopping distance is shown in the following Fig 7. From this graph, it can be seen that higher charging pressure provides more torque and less stopping distance with higher rate of deceleration. This is due to the fact that same system will run with higher pressure and larger amount of energy will be consumed to attain this pressure. Whereas lower charging pressure gives less torque and takes more time to stop the bicycle with lower deceleration.

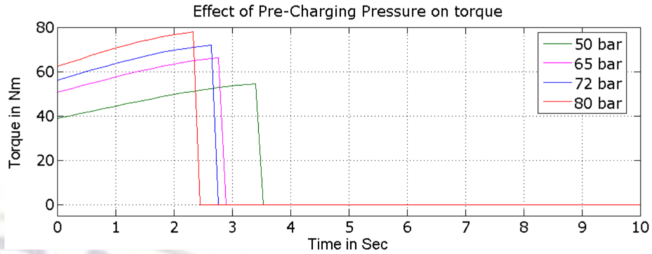


Fig. 7. Effect of Pre-charging pressure on Accumulator

Result of above simulation with Eaton Char-Lynn J 129 motor is listed below,

Table 4. Result of variation of Pre-charging Pressure in Accumulator

| Pre-charging Pressure | Torque (Nm) | Stopping Time (sec) | Deceleration ($m/s^2$) |
|---|---|---|---|
| 50 bar | 54.6 | 3.56 | 3.043 |
| 65 bar | 65.02 | 2.92 | 2.8 |
| 72 bar | 73.4 | 2.8 | 2.92 |
| 80 bar | 78.3 | 2.4 | 3.56 |

From the above simulation, we can see that pre-charging pressure of 72 bar gives fair result considering braking period. From the above simulation it can be noted that nearly 92% of kinetic energy can be stored on the accumulator. And same can be given to the motor for propelling mode [6].

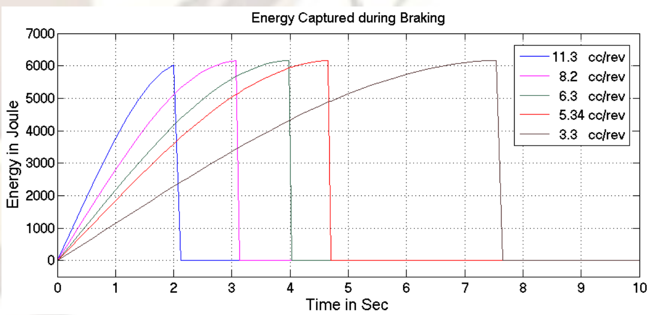


Fig. 8. Effect of Displacement of pump on Energy stored

The above figure shows the rate of energy stored in the accumulator for different pumps. Slope of curve of pump with higher displacement is steeper while the slope is leaner in case of lower displacement pump.

## 4. Conclusion

In this paper, a simple hydraulic circuit is proposed which can be remotely actuated with the help of electric circuit. Based on different manufacturer's catalogue a variety of components are selected to suit the hydraulic circuit. The relationship among the components involved in regenerative braking and propelling modes have been analyzed. Simulation model for the hydraulic regenerative braking system has been established. Influences of the main factors to the braking performance were investigated. Based on the above analysis final component specification can be given as,

Table 5. Final Specification of the Components

| | |
|---|---|
| Hydraulic fixed displacement Gear Pump (2) and Motor (3)<br>Eaton Char-Lynn Spool valve J series 129 | |
| • Volumetric Displacement | 8.2 $cm^3$/rev |
| • Volumetric Efficiency | 0.95 |
| • Maximum Pressure | 140 bar |
| Hydraulic Bladder Type Accumulator<br>Bosch Rexroth 1 gallon accumulator, HAB–5X ASME | |
| • Nominal Size | 4 liters |
| • Maximum pressure | 208 bar |
| • Approx. Weight | 15 kg |
| Reservoir (container type) | |
| • Maximum Volume | 5 liters |

From the above specification the paper provides a platform for implementing a hydraulic regenerative bicycle. Implementation of this will result in less human effort for complete driving cycle. Lesser effort will encourage driver to choose bicycle over fueled vehicle. Also the proposed system does not add much weight to the existing system. Since all the components used in the system are standard the maintenance also becomes simple.

Disadvantage of the system is that it is costly. It can cost thrice the amount of a bicycle. But with help of further development and research in the same area this cost can be lowered to an economical value.

## 5. Acknowledgement:

I have been able to complete this study with the help of a few but very important people who had trust in my abilities. I would like to thank Prof. A. R. Suryavanshi, who guided me in this paper and Ms. Priyanka Gujar who helped me in completing this paper successfully.

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