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ENERGY EXTRACTION FROM CONVENTIONAL BRAKING SYSTEM OF AUTOMOBILE

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ABSTRACT
Optimization of power consumption is an important subject in the design of automobile. The conventional braking (friction brake) system losses considerable amount of energy during car drive. A model of braking system is designed and constructed to extract and store energy during the braking of a car. Gaseous fluid is compressed in cylinder by a high pressure liquid to store the energy of brake. A positive displacement pump driven by the extraction of energy from break is used to supply the high pressure liquid. During braking the pump is clutched with the power train of the car. The pump utilizes the inertia energy of the car to compress the gaseous fluid. This stored energy can be used to enhance the acceleration of car and to run other accessories of the car. A performance test of the brake model is conducted and can be found that, during brake approximately 60% of inertia energy can be saved.

Keywords: Braking System, Inertia Energy Conservation, Compressible Fluid, Friction Brake.

1. INTRODUCTION
Motor vehicle has been the heart of human transportation since the dawn of its creation. Many advances have been made to make the motor vehicle more desirable and friendly for the millions of users throughout the world. It is our goal to design a device that can make their commute an economic one. The Energy extraction from conventional braking system of automobile is a device that can do so by reducing the overall energy required to use. Brake energy is a energy that stops an engine. There are also other opposing forces such as aerodynamic drag force and rolling force. Research of William H. Crouse, "Automotive Mechanics"[1] showed that almost 50% of the total energy was lost as brake energy although this percentage is a bit different from different types of vehicles. Wendel at al. [2] described in Michigan clean fleet conference, Hydraulic Regenerative Braking System has a good power density of 1458 W/Kg and efficiency about 85%. So, this system is more efficient than electric energy storage device.

In 1996 University Wire performed a research onelectric regenerative braking system [3]. In 2002 a new braking system called hydraulic launch assisted to make a stop-and-go driving for large trucks more efficiently by capturing energy [4]. Advanced Technology department at Eaton's Fluid Power Group in 2009 begins a test of Rexroth Hydraulic Hybrid Technology in Refuse Trucks [4] It is sponsored by the New York State Energy Research and Development Authority (NYSERDA), this evaluation project identifies vehicle fleets which integrate technologies such as HRB (Hydraulic Regenerative Braking system), have high potential for reducing fuel consumption and emissions. The hydraulic hybrid evaluation is a part of a larger program carried out by DSNY that will demonstrate the impact of utilizing multiple alternative drive technologies. In April 2009 Artemis Intelligent Power [5] converted a BMW 530i to capture the energy mechanically resulted from braking (aka "regenerative braking"), and use it in an electrically-hybridized car fashion [6].

2. PRODUCT DEVELOPMENT PROCESS
Many decisions are needed to be made in order to produce the most desirable and affordable model to make the highest efficiency and the most unique device. Process has four distinct phases: the Concept Phase, the Design Phase, Mathematical modeling Phase and the Construction Phase. In the Concept Phase, we defined the problem of losing energy while braking on a motor vehicle. We then conceptualized different ways of using that energy with different regenerative braking systems. Through research and customer surveys, we entered the Design Phase knowing consumer preferences. We generated designs based on known preferences, constraints, and parameters. We then made a CAD drawing of our design. We analyzed our model from the viewpoint of the consumer and manufacturer and did mathematical analysis of the optimal designs. After

reviewing our results, we hypothesized how we would start the Construction Phase.

2.1 Design Requirements

There are some requirements that needed to produce a product that is both feasible and optimal. There are also some constraints, both geometric and engineering that are also needed to be satisfied. The following list describes these requirements and constraints:

1. Store energy while braking

This is the main requirement and the overall objective of the device and must be suitable to meet the customer's needs.

2. The system must be fitted on the vehicle for which it is designed

This is one of the most difficult constraints to achieve because we are dealing with a confined spacing. The system contains a few cylinders and other components which are to be fitted on the longest part of the car, particularly between the two axles of wheels.

3. Light weight

The importance of having a light weight design is driven by the customer's desire to have a car that is more maneuverable and more portable. This is also a direct trade off with how much energy can be stored in the cylinders.

4. Good stopping range

The stopping range is important because the system needs to be usable in real life situations. The product can be optimized to have the shortest stopping distance using dynamic analysis.

5. Safe to user and environment friendly

Safety is always a very important aspect whenever there is a consumer product. This requirement will be addressed during the design.

6. Reliable

It is important to have a product reliable and this requirement will affect the long term production and needs to be maintained in high regards.

7. Manufacturability

In order to make anything profitable, it needs to be easily manufactured, hence important of having a product that can be made easily and economically.

2.2 Methodology

Inertia energy of a car is stored as a compressed fluid energy while braking is done. A clutch is used as a brake shoe. During braking this clutch will engage the driveline of the system, then the pump will be activated and it will force hydraulic fluid out of a low pressure cylinder (Reservoir) to a high pressure cylinder. This hydraulic fluid then compress the gaseous fluid in the cylinder and the energy will be stored. This energy can also be used to run a compressor for air conditing, lube oil motor or other hydraulic system.

Power is transmitted from the car drive train to the speed increasing gear box through the clutch. So pump is started to rotate with an increased speed which in turn moves fluid to the accumulator and energy can be stored within a short time, then the car will stop.

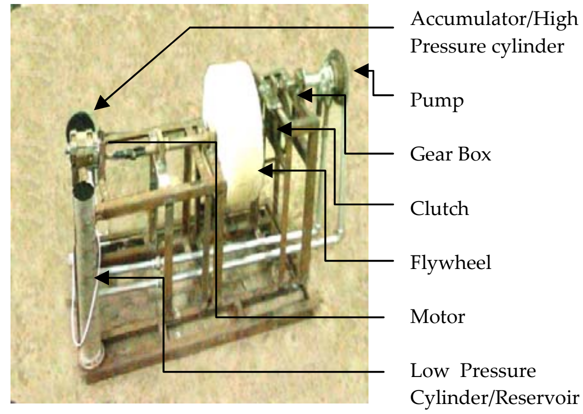


Fig 1. Experimental setup of the system

2.3 Design Parameters

Following components are used in model

1. Flywheel
   - Diameter = 15in
   - Width = 6in
   - Material: concrete
2. Gear box
   - Diameter of small gear = 1.5in
   - Diameter of big gear = 7in
3. Motor: 3-phase ac motor
4. Clutch: 50cc Honda clutch
5. Pump: Oil pump of medium size pick up car
6. Accumulator / high pressure cylinder
   - Volume = 75 in^3
7. High pressure cylinder/Reservoir
   - Volume = 100 in^3

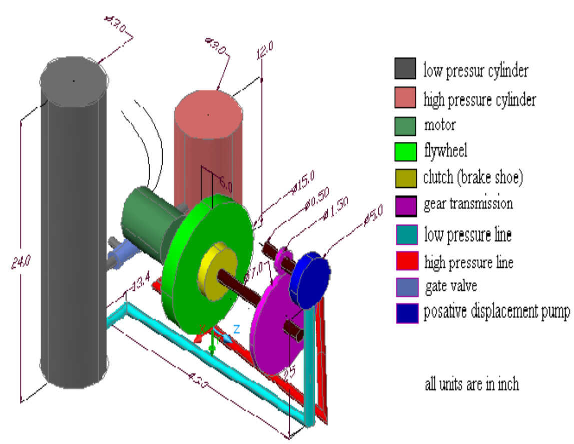
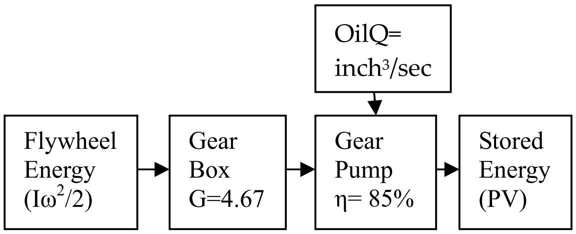


Fig. 2 Components of the model

3. MATHAMATICAL MODELING

3.1 THEORETICAL DERIVATION OF THE NECESSARY EQUATIONS

The flow diagram of energy storing system is shown below:



Power flow across the pump,

$T_p*\omega_p = \Delta P*Q'/\eta$

$=> T_p * 2\pi n = \Delta P*Q*n/\eta$

$=> T_p = \frac{\Delta P*Q}{2\pi\eta}$

but $T_i/T_p = G = D_1/D_2 = 7/1.5 = 4.67$;

$=> T_i = -I\alpha = \frac{\Delta P*Q*G}{2\pi\eta}$

$=> I\alpha = -\frac{\Delta P*Q*G}{2\pi\eta}$

$=> \alpha = -\frac{d\omega}{dt} = -\frac{\Delta P*Q*G}{2\pi\eta I} = -\frac{Q*G\,(P-P_{atm})}{2\pi I\eta}$

Assuming that,
Air compression processes is isothermal process, so pressure volume relation is –
$PV = P_0V_0$
here, $P_0 = P_{atm}$

$=> \frac{d\omega}{dt} = -\frac{Q*G(\frac{P_0V_0}{V} - P_{atm})}{2\pi I\eta}$

$$\frac{d\omega}{dt} = -\frac{Q*G*P_{atm}(\frac{V_0}{V} - 1)}{2\pi I\eta} \quad (1)$$

3.2 Expression of V_O/V

Change of Energy in Fly wheel = Energy Stored in Cylinder

$1/2\, I(\omega^2 - \omega_o^2) = 1/\eta \int_{V_0}^{V} P\,dV$

$= \{RT*\ln(V/V_o)\}/\eta$

$V_o/V = e^{-\frac{I\eta}{2 P_{atm}*V_0}*(\omega^2 - \omega_o^2)}$

$$V_o/V = e^{-\frac{(I\eta\omega_o^2)}{2 P_{atm}*V_0}*(\frac{\omega^2}{\omega_o^2} - 1)} \quad (2)$$

From equation (1)

$\frac{d\omega}{dt} = -\frac{Q*G*P_{atm}\left(e^{\left\{-\frac{(I\eta\omega_o^2)}{2P_{atm}*V_0}*\left(\frac{\omega^2}{\omega_o^2}-1\right)\right\}}-1\right)}{2\pi I\eta}$

when t = 0, $\omega = \omega_o$ &
t = t, $\omega = \omega$
After integrating

$$\int_{\omega_o}^{\omega} \frac{d\omega}{1 - e^{\left\{-\frac{(I\eta\omega_o^2)}{2P_{atm}*V_0}*\left(\frac{\omega^2}{\omega_o^2}-1\right)\right\}}} = \frac{Q*G*P_{atm}}{2\pi I\eta}\int_0^t dt \quad (3)$$

Equation (3) represents the variation of angular speed ω with respect to time.

3.3 Time Required to Stop The Wheel:

At the time to stop the flywheel, t = T then ω = 0;
From Equation no (3)

$\frac{Q*G*P_{atm}}{2\pi I\eta}\int_0^T dt = \int_{\omega_o}^{0} \frac{d\omega}{1 - e^{\left\{-\frac{(I\eta\omega_o^2)}{2P_{atm}*V_0}*\left(\frac{\omega^2}{\omega_o^2}-1\right)\right\}}}$

$T = \frac{2\pi I\eta}{Q*G\,P_{atm}}\int_0^{\omega_o} \frac{d\omega}{a^{\left(1-\frac{\omega^2}{\omega_o^2}\right)} - 1}$

$T = \frac{2\pi I\eta}{Q*G\,P_{atm}}\int_0^1 \frac{\omega_o d\omega_r}{a^{(1-\omega_r^2)} - 1}$

For getting finite value of integration assuming the limit 0 to 0.991

$= \frac{2\pi I\eta\omega_o}{Q*G\,P_{atm}}\int_0^{0.991} \frac{d\omega_r}{a^{(1-\omega_r^2)} - 1}$

$$= 2.244 \int_0^{0.991} \frac{d\omega_r}{2.9614^{(1-\omega_r^2)} - 1} \quad (4)$$

= 2.244*3.064

= 6.8768 sec

Here

$a = e^{\frac{(I\eta\omega_o^2)}{2 P_{atm}*V_0}} = 2.9614$

$\omega/\omega_o = \omega_r$

$d\omega = \omega_o * d\omega_r$

When ω = 0 then $\omega_r = 0$
$\omega = \omega_o$ then $\omega_r = 1$

Theoretical stopping time of the fly wheel T = 6.8768 sec for N = 200 rpm

3.4 Volume Calculation

At the time to stop the flywheel, t = T & ω = 0; $V = V_2$
For ω = 20.984, N = 200rpm
From Equation (2)

$V_o/V = e^{-\frac{(I\eta\omega_o^2)}{2 P_{atm}*V_0}*(\frac{\omega^2}{\omega_o^2} - 1)}$

So $V_o/V_2 = e^{-\frac{(I\eta\omega_o^2)}{2 P_{atm}*V_0}*(\frac{\omega^2}{\omega_o^2} - 1)}$

$= e^{-\frac{[illegible]}{[illegible]}(0 - 20.984^2)}$

= 2.9768

$V_2 = 75/2.9768 = 25.1958\ in^3$

$P_2 = P_1V_1/V_2 = 43.759$ psi

Energy Input
$E_{in} = 1/2\ I\omega_o^2 = 0.5*0.7258*20.924^2 = 159.8451$ J

Energy Stored
$E_{st} = -PoVo*\ln\frac{V}{V_o} = -101325 * 75*0.0254^3 *\ln\frac{25.1958}{75}$

$= 135.8451$ J

For $\omega = 15.7$ N = 150 rpm
when $\omega = 0$ and $V = V_2$
From Equation (2)

$$V_o/V = e^{-\frac{(I\eta_p\omega_o^2)}{2 P_{atm} V_o}\left(\frac{\omega^2}{\omega_o^2}-1\right)}$$

So $$V_o/V_2 = e^{-\frac{(I\eta_p\omega_o^2)}{2 P_{atm} V_o}\left(\frac{\omega^2}{\omega_o^2}-1\right)}$$

$$= e^{-\frac{0.7258*0.85}{2*101325*1.23e-3}(0-15.7^2)}$$

= 1.8417J

$V_2 = 75/\ 1.8417 = 40.729\ in^3$

$P_2 = P_1V_1/V_2 = 27.0732$ psi

Energy Stored
$E_{st} = -PoVo*\ln\frac{V}{V_o} = -101325 * 75*0.0254^3 *\ln\frac{40.7289}{75}$

= 76.09241J

Energy Input
$E_{in} = 1/2\ I\omega_o^2 = 0.5*0.7258*15.7^2 = 89.451$J

Table 1: Theoretical developed Pressure, Volume and Stored Energy

Obs No	N, rpm	P_2 psi	V_2, in^3	T sec	E_{in} (J)	E_{st} (J)	Friction Loss	% of Energy Stored
1	200	43.7	25.2	6.8	159	136	24.1	85
2	150	27.1	40.7	5.1	89.4	76.2	13.3	85

4. RESULT AND DISCUSSION

4.1 Data Collection

Flow rate and efficiency of the rotor pump are taken from J. S. Cundiff [7]
Flow Rate $Q = 4.53\ in^3/rev = 7.4233x10^{-5}\ m^3/rev$
Average efficiency η_p =85%
P_{atm} = 101325 Pa, Gear Ratio = D_2/D_1 = 7/1.5= 4.67
Density of concrete, $\rho = 2000\ kg/m^3$
Diameter of flywheel D =15in = 15*0.0254 = 0.381 m,
Width, L = 6in = 6*0.0254 = 0.1524m

Table 2 : Data Collected

No of Obs	Rotation of wheel N_w (rpm)	Pressure raise in accumulator ΔP (Psi)	Time require to stop the wheel T(sec)
1	200	15.5	27
2	150	5.5	15

4.2 Calculation

Table 3: Calculated Data

No of Obs	Volume V_2 $Inch^3$	Input Energy E_{in}(J)	Stored energy, E_{st} (J)	Friction Loss (J)	% of input energy stored
1	36.75	159.9	88.2	71	55.5
2	55.1	89.5	38.3	51.17	43

Assumptions:

- Isothermal Gas Compression process
- Neglecting Aero and rolling friction Force.

Initial Volume $V_o = 75\ inch^3 = 1.23x10^{-3}\ m^3$
Final pressure $P_2 = \Delta P + P_{atm}$ = 30.2 psi
Final volume $V_2 = P_1V_1/P_2$
= (14.7*75)/30.2 = 36.75 $inch^3$

Mass of flywheel ,
$m_w = \rho V$ + weight of Rod
= 2000* π*0.1905^2 *0.1524 + weight of Rod
= (35+5) Kg
= 40 Kg

Moment of Inertia,
$I = ½*m_w (D/2)^2$
$= 0.5*40*0.1905^2$
$= 0.7258\ Kgm^2$

Energy Input
$E_{in} = 0.5*I*\omega_o^2$
$= 0.5*0.725*20.9485^2$
= 159.9485J

Energy Stored
$E_{st} = -P_0V_0\ln(V_2/V_1)$
= -101325 *1.23e-3 *ln (36.75/75)
= -124.63 ln 0.49
= 88.904 J

Friction Loss = E_{in} - E_{st} =71.0445 J

% of Input energy is stored = (88.904/159.9485)*100%
= 55.5828%

Observation 1
Energy Input = 159.247J
Theoretical Time Required to stop the wheel= 6.8768 sec

Theoretical Energy Stored = 135.8451J
Theoretical Frictional Loss = 24.1019J
Experimental Time Required to stop the wheel = 27 sec
Experimental Energy Stored = 88.204J
Experimental Frictional Loss = 71.0429J
% of Input energy is stored (Theoretical) = 85%
% of Input energy is stored (Experimental) = 55.58%

$$\% \text{ of Error} = \frac{(E_{st})_t - (E_{st})_e}{(E_{st})_t} = \frac{135.8451 - 88.204}{135.8451} = 34.55\%$$

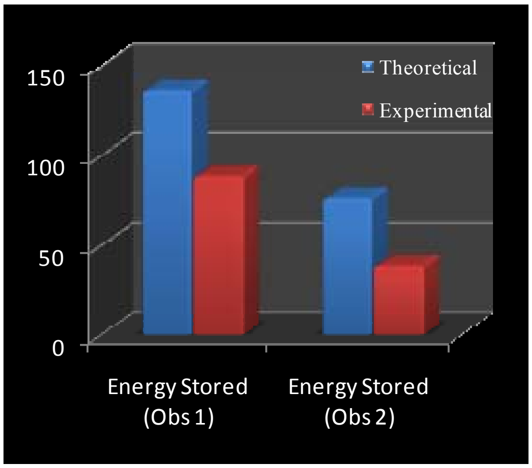


Fig. 3 Stored energy comparison (Theoretical Vs Experimental)

4.3 Discussion

In regenerative braking system works within our expected range. Percentage of input energy stored in theoretical is 85% and the experimental result is 55.5%. It has almost reached our theoretical results. But there are some deviations. These deviations occur due to the following reasons.

1. akage in the Pump:
2. friction in the whole drive train:
3. vibration in the flywheel:
4. leakage in the accumulators and joints:
5. unavailability of the designed components with desired rating in local market:

This deviation will be less in prototype. Because in prototype friction loss will be less, and vibration will be less as all the components will be designed & manufactured as per need.

5. CONCLUSION

In this work, a model of regenerating braking system is designed, manufactured and tested. The data is then compared with theoretical calculation. Two observations are made with rotational speed of the motor. It can be observed that for high speed the percentage of energy store is high and for low speed it is low. This is quite natural that the system loss due to friction and other possible causes is almost same for all rotational speed. Therefore it affects the lower rotational speed. Hopefully much higher rotational speed of motor in model test will increase the percentage of energy store.

6. RECOMMENDATIONS

To increase the performance of the model the following modifications can be made:
1. In our project regeneration was not done. It can be done by using Hydraulic motor unit.
2. By increasing the number of positive displacement pumps or using more power pumps braking could be done more rapidly.

More sophisticated hydraulic positive displacement pump could be made.

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8. NOMENCLATURE

Symbol	Meaning
E_{st}	Energy stored in the Cylinder
E_{in}	energy in the flywheel
m_w	Mass of the flywheel
D	Diameter of the flywheel
L	Height of the flywheel
I	Moment of Inertia
α	Angular Acceleration of the Flywheel
ω_o	Initial Angular velocity (velocity at the start of the braking)
ω	Instantaneous angular velocity
N_w	Rotational speed of the flywheel
N_p	Rotational speed of the pump
T_w	Torque in the Flywheel shaft
T_p	Torque in the Pump shaft
D_1	Diameter of the big gear
D_2	Diameter of the small gear
G	Gear ratio
P_o	Initial pressure in the cylinder
P	Instantaneous pressure in the cylinder
P_2	Final Pressure
Δp	Instantaneous change of pressure in the cylinder
V_o	Initial volume in the cylinder

V	Instantaneous volume in the cylinder
V_2	Final Volume
Q	Rated flow rate of pump(m^3/rev)
Q'	Flow rate (m^3/sec)
t	Time
T	Stopping time
η	Efficiency of pump

9. MAILING ADDRESS

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