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Regenerative Braking in Automobiles

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Abstract:

Normally, the braking system for a car iscentered on hydraulic braking technology. However, thistraditional braking approach causes a lot of wastage of energysince it produces undesirable heat energy during the braking action.Consequently, the invention of regenerative braking in electricvehicles has overcome these disadvantages moreover it helpsto save energy and increase efficiency for the vehicles.Wheneverbrakes are applied, a significant amount of kinetic energyislost in the form of heat energy due tofriction between brake pads and rotor. RegenerativeBraking System recovers kinetic energy as much aspossible that is wasted during the process of braking. The energy is stored and then released under acceleration. Thispaper highlights the two different methods of recoveringenergy, by converting it intoeither electrical or mechanical energy. The kinetic energygets converted into electrical energy with the help ofelectric motor while flywheel harnesses the kineticenergy by converting it into mechanical energy.

Keywords —**Regenerative Braking, Energy recovery system, Electric motor, Generator, Batteries, Flywheel, HEV, EV.**

I. INTRODUCTION

The electric vehicle (EV) invention has been a miracle, also called as a green vehicle as it produces zero emission to the air which means there is no release of toxic gasses from the car which causes the ozone layer depletion. Nowadays, the number of EV is increasing according to the market demand. Besides, the Government's regulations to the production of electric car are getting more serious.Each step is taken by the world to save the Planet Earth from the excessive air pollution and the recession on the natural resources like crude oils and natural gasses in the earth. Today, there have been a lot of technological advances in fields of control technology and integrative technology. But, the limitation of the driving range has still been an obstacle in development of the Electric Vehicles. By using regenerative braking in EVs and HEVs, this hurdle of driving mileage can be tackled which improves the driving limit by 8-25% [(11), (12)].The traditional braking system in a vehicle is been replaced by regenerative braking system as the former only utilises friction for kinetic energy dissipation in order to completely stop a vehicle. Many studies show that, of the total energy required for the operation of a vehicle, about a third to half evaluation, the kinetic energy is anexcess energy when the electric motor of the vehicle is in the braking conditionsince dissipation of energy as heat takes place and hencethere is loss in the overall energy of the vehicle. In the case of the EVs and EVs, this wasted energy can actually be converted to a useful energy. As a result, regenerative braking has been implemented in the car braking system to recollect this wasted energy from the vehicle. Additionally,driving condition also play a part in the total energy recovered.Generally,regenerative braking is more effective in city driving because of a lot of braking action rather than highway.There are many advantages of regenerative braking over the traditional braking system such as:

- More control over braking
- More efficient and effective in stop-and-go driving conditions
- Prevents wear on mechanical brake systems
- Better fuel economy
- Save energy

II. BASIC THEORY OF VEHICLE BRAKING

Braking theory and design principles of the conventional vehicle by using a frictional mechanism are well established. Itemphasizes on the distribution of total braking force on front and rear in order to attain short braking distance and prevent the rear wheel from being locked earlier than the front wheel is locked.A brief description of traditional vehicle braking theory is added in this paper as followings for an easy understanding for readers.

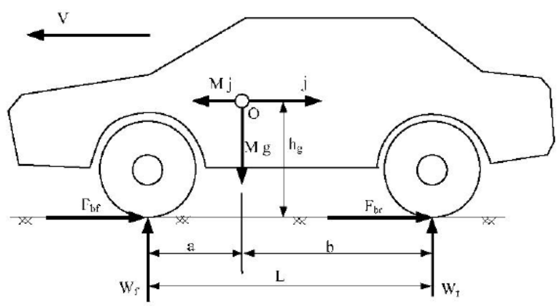

Figure 1: Forces acting on the while braking

Fig 1 shows the forces acting on the vehicle during braking on a flat road surface, where the resistance due to rolling and aerodynamic drag are ignored. The normal forces $W_f$and W_r, acting on the front and rear wheels can be expressed as:

$$W_f = \frac{Mg}{L}(b + \frac{j}{g}h_g)$$
$$W_r = \frac{Mg}{L}(a - \frac{j}{g}h_g)$$

where j is the vehicle deceleration in m/s^2, $F_{bf}$and F_{br} are braking forces acting on the front and rear wheels, and M is the mass of vehicle in kg, and other parameters shown in Fig.1 where,O is the centre of gravity of the vehicle. Normally, the deceleration of the vehicle depends on the total braking force as:

$$j = \frac{F_b}{M} = \frac{F_{bf} + F_{br}}{M}$$

Ideally for optimal performance of braking, thedesired braking forces i.e.F_{bf} andF_{br}, should be proportional to the corresponding vertical loads ($W_f$andW_r),as shown in Fig. 1.
Thus, we have:

$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r} = \frac{b + \frac{j}{g}h_g}{a - \frac{j}{g}h_g}$$

When the braking forces is applied on the front and rear wheels follow the above equation, both the front and rear wheels will be locked simultaneously as the braking force applied reaches the maximum friction capability in the contact area of the tire and road. At this instant, the deceleration of the vehicle can be expressed further as:

$$j = \frac{F_{bf} + F_{br}}{M} = \frac{(W_f + W_r)\mu}{M} = \frac{Mg\mu}{M} = g\mu$$

where μ is the adhesive coefficient between tire and road.It is defined as the ratio of the maximum braking force theroad can supply to the vertical load. The equation can be expressedfurther as:

$$\frac{F_{bf}}{F_{br}} = \frac{b + \mu h_g}{a - \mu h_g}$$

Using these equations, the ideal braking forces applied on the front and rear wheels on the roads with a various adhesivecoefficient (vehicle deceleration) are shown in Fig. 2, which are markedI_L for full load and I_u for unloaded. These curves are parabolic. In designing of mechanical brakingsystem, implementation of the parabolic braking force distribution will tend to very complex structure. Hence, inconventional vehicles, a straight-line braking force distribution is usually employed as marked in Fig. 2. In this case, only on one road condition (point A, u=0.8 in the example of Fig. 2), the front and rear wheels will be locked instantaneously.When braking on the road with adhesive coefficient less than thisvalue, the front wheels will be locked before the rear wheels. This leads to a great directional stability.However, when braking on the road with large adhesivethe coefficient (μ >0.8), the rear wheel willbrakingforces acting on front and rear wheels, and M is the mass to be locked before the front wheels lacked, which causes instability of vehicle. This instability tendency will worsenwhen the vehicle is unloaded, where the rear wheels haveless vertical load, and will be locked much easily, asdemonstrated by point B in Fig. 2.Usuallyin actual practice,the brake system ofpassenger cars is designed such that the rear wheels willnever be locked. This results in small braking forceon the rear wheels as demonstrated by the straight-line labelled β inFig.2. Nevertheless, this design has the disadvantage that the actualbraking force distribution is far from the ideal;hence,it leads to low road adhesion utilization and low utilizationefficiency ofpressure of the front wheel. Because of this, some brakedesign regulations insist on the minimum rear braking force,typical one is the BCE regulation illustrated by the curvelabelled ECE-regulation [12].

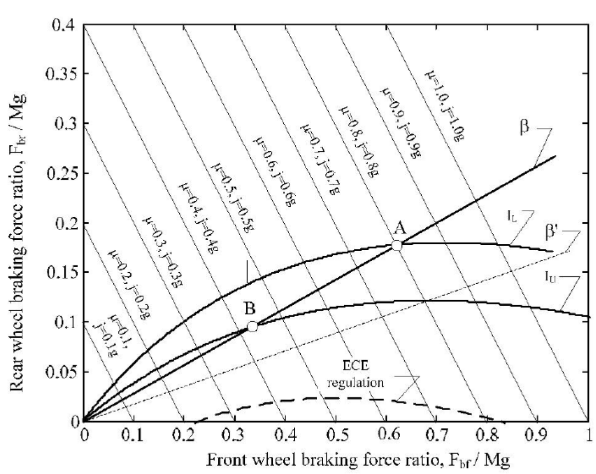

Figure 2: Ideal braking and real braking force on the front and rear wheels, and theminimum braking force on rear wheels with loaded condition (ECE-regulation)

In design and developmentof a hybrid braking system for EVs and HEVs, the principle mentioned above should be followed in order to ensure the vehicle has a good braking performance. At the same instant, it should be able to recover as much braking energy as possible.

III. REGENERATIVE BRAKING USING ELECTRIC MOTOR

Electric vehicles (EVs) and Hybrid Electric Vehicles (HEVs) use an electric motor as asource to propel themselves. As known, when the motor is madeto run in reverse direction itbehaves as a generator. Similarconcept or principle is utilized for regenerative braking.When braking action is to be done, motor switches itself to generatormode. The generator then captures the kinetic energy of the wheel viaa drivetrain. Consequently, it transforms the kinetic energy intoelectrical energy which is then stored in a battery for further use.On the other hand, generator resistance produced from theelectricity generated, slows down the vehicle. The greater the power ofMotor or Generator in generator mode, larger will be the amount ofkineticenergy recovered. The capacity of battery to store the energy is also a factor that affects the amount ofenergy recuperated. When the torque generated by the generator is less as compared to the required braking torque,it is enhanced by a friction brake.

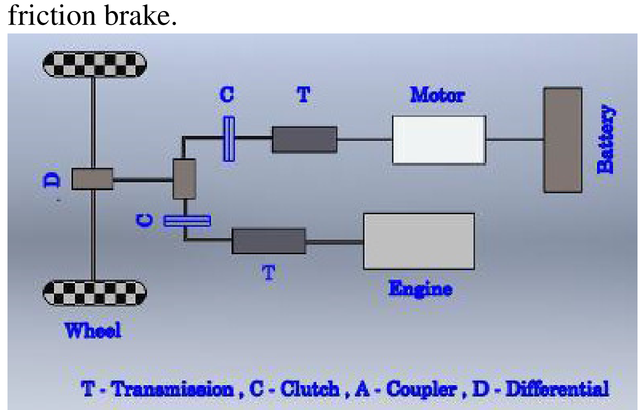

Figure 3: Regenerative Braking using motor and Battery as an energy storage system

IV. REGENERATIVE BRAKING USING FLYWHEEL

The flywheel is a heavy rotating mass which is used to store the kineticenergy or the mechanical energy of rotating wheel in the form of rotational energy.This process of recoveringenergy is more efficient. The losses involved during energytransformation are avoided because the energy is beingtransmitted in the form of mechanical energy throughout the cycle. Incase of recovering the energy through motor/generator andbattery system, many energy losses occur as mechanical energy isbeing transformed into electrical energy while charging thebattery and during discharging, the electrical energy getsconverted into mechanical form.The energy generated is expressed as:

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

where,

E=rotational energy of flywheel
I=moment of inertia of flywheel
ω=angular velocity of flywheel

The energy stored by the flywheel depends upon itsmass, radius and rotational velocity. Hence, the maximumenergy stored by flywheel can be enhanced by increasingmoment of inertia and angular velocity of the flywheel. In orderto recover energy or to start energy transfer throughflywheel, the angular momentum of the flywheel must be varied. For varyingangular momentum, angular velocity or moment of inertiamust be varied constantly. Thus a Continuous VariableSystem (CVT) is used to transmit the power. Itconsistsof two pulleys which are connected by a belt. One Pulleyis acts as a driving pulley whereas the other acts as a drivenpulley. The continuous movement of the sheaves of pulleychanges the effective diameter of belt and hence gear ratio changes accordingly.Flywheel is connected to one end of the CVT whereas it'sanother end is linked to driving axle i.e. the wheel.The CVT changes the angular velocity of theflywheel establishing different gear ratio between flywheeland wheel. The range of CVT determines the maximumangular velocity that can be achieved by a flywheel.During normal mode, vehicle is powered by the engine byengaging the clutch between engine and variabletransmission. In regenerative braking system, flywheel isengaged to the transmission while the engine clutch isdisengaged. The variable transmission continuously variesgear ratio so as to speed up the flywheel. The angularvelocity of wheel gets reduced and that of flywheel increases.Thus, the energy is stored in flywheel in the form of mechanical energy. In energy recoverymode or accelerating mode, flywheel clutch is engaged by establishing suitable gear accelerating mode, ratio between flywheel and wheel.The gear ratio varies continuously to speed up thewheels. Thus, the vehicle is powered by a flywheel by shuttingdown the engine.Thus, the energy is retainedby the flywheelassisted by a regenerative braking system. Flywheels have a highspecific power as compared to the conventional battery andthus prove to be a better energy storage system.

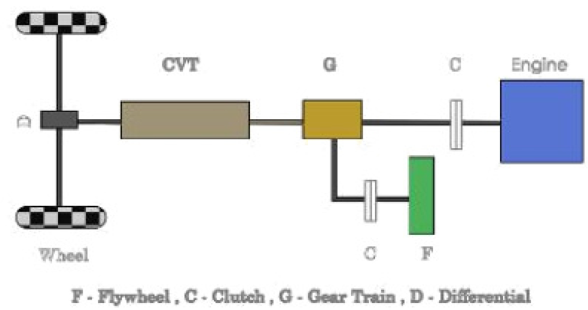

Figure 4: Flywheel-Regenerative Braking System

V. ADVANTAGES OF REGENERATIVE BRAKING

1. Fuel economy is improved as it lowers the fuelconsumption.
2. Reduce the carbon footprint and thus environmentfriendly.
3. Improved vehicle performance as it boosts theacceleration instantly.
4. Regenerative braking system reduces the overallwork done by the engine and therefore reduces thewear of engine parts.
5. Regenerative braking complements the frictionalbraking and reduces the wear and tear of brakeassembly parts.

VI. FLYWHEELS: A BETTER ALTERNATIVE TO BATTERIES

1. Flywheel has better efficiency ascompared to battery as the losses do not occurduring energy transformation.
2. It has higher specific power and thus can deliverenergy at high rate.
3. They are less sensitive to the temperature variationwhereas conventional batteries

experiences powerfades at high temperatures.
4. The operating life or cyclic age of flywheel is more as compared to battery.
5. They have comparatively less impact on theenvironment and are easy to recycle.

VII. THE FUTURE FOR REGENERATIVE BRAKING

There are a number of subjective decisions one has to make concerning the regenerative system profile. Some people like regenerative system to work all the way to 0 mph, bringing the car to stop. Some like to coast that last 2 to 3 mph. almost everyone likes the car to regenerate when you take your foot off of the throttle pedal, but there are some who would prefer the car to coast when one does this. They would prefer the regenerative system to be tied to the application of the brake pedal. Almost everybody likes the more aggressive regenerative system, but a few are more comfortable with a traditional ICE-like compression braking and coast-down profile.

One day everybody will drive electric cars and regenerative system will be a big part of what will make them fun to drive, efficient, and safe. The recent research and development to integrate the powertrain and brake systems to provide better traction and stability control can only be made easier by the use of electric drive systems. Traction control is a much simpler problem to solve when one has precise and instant control of torque through the AC induction motor controller. Integrating the antilock braking systems and motor controller would allow the motor to take over more of the vehicle braking.

VIII. CONCLUSION

The energy wasted during braking can be captured andreused by using Regenerative braking system, which is one of the most effective and emergingtechnologies to save energy lost. The above discussedstorage system proves flywheel as a better energy storagesystem. There is always a scope for improvement in terms of technology. Thus, the effort should be made to layout anappropriate design of flywheel which can withstand a large amountof the stress developed in flywheel. Also, the research should be made to implement such a material for the flywheel which has good strength and comparatively less weight sothat they can be feasible for the practical aspects of vehicle.Some modern flywheels are made of carbon-compositematerials and are proved to be more feasible and reliable.By introducing an efficient transmission system, it wouldincrease the overall efficiency of regenerative braking.Further research could help in making this technology morereliable and efficient.

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