

A Mechanical Regenerative Brake and Launch Assist using an Open Differential and Elastic Energy Storage

David H. Myszka, Andrew Murray, Kevin Giaier, and Vijay Krishna Jayaprakash
University of Dayton

Christoph Gillum
Stress Engineering Services Inc

ABSTRACT

Regenerative brake and launch assist (RBLA) systems are used to capture kinetic energy while a vehicle decelerates and subsequently use that stored energy to assist propulsion. Commercially available hybrid vehicles use generators, batteries and motors to electrically implement RBLA systems. Substantial increases in vehicle efficiency have been widely cited. This paper presents the development of a mechanical RBLA that stores energy in an elastic medium. An open differential is coupled with a variable transmission to store and release energy to an axle that principally rotates in a single direction. The concept applies regenerative braking technology to conventional automobiles equipped with only an internal combustion engine where the electrical systems of hybrid vehicles are not available. Governing performance equations are formulated and design parameters are selected based on an optimization of the vehicle operation over a simulated urban driving cycle. The functionality of this elastically-based regenerative brake device has been demonstrated on a physical prototype.

CITATION: Myszka, D., Murray, A., Giaier, K., Jayaprakash, V. et al., "A Mechanical Regenerative Brake and Launch Assist using an Open Differential and Elastic Energy Storage," *SAE Int. J. Alt. Power*, 4(1):2015, doi:10.4271/2015-01-1680.

1. INTRODUCTION

A conventional automobile only uses 15-30% of the energy available within the fuel [1]. Increasing fuel prices and control of emissions is prompting automotive manufacturers to increase fuel efficiency. One solution is hybrid vehicles that provide a 60% to 100% gain in fuel economy [2], but only make up approximately 3% of the current market [3]. The vast majority of vehicles on the road are still powered by conventional internal combustion (IC) engines. An increased focus on improving the fuel efficiency in conventional IC vehicles fostered recent developments including the use of alternative fuels [4], reduced friction within engines [5], and continuously variable transmissions [6].

Regenerative braking is the harnessing of kinetic energy typically lost due to braking and converting it to a another form of energy to be used later [7]. Hybrid electric vehicles use a regenerative brake and launch assist (RBLA) system that employs a motor/generator to convert the kinetic energy of the vehicle into electricity when the car is braking. This energy is stored in the batteries and used to propel the vehicle later. Without large battery packs, propulsion motors, hybrid-style RBLA technology is not directly applicable to a conventional vehicle. However, a mechanical RBLA may allow conventional automobiles to benefit from this technology. Further, heavy trailers that do not have a drive train could benefit from RBLA devices.

Various mechanical methods for harnessing and storing the energy have been used as mechanical versions of regenerative braking do not suffer from energy-mode conversion losses. The Kinetic Energy Recovery System utilizes regenerative braking and stores the energy in a carbon-fiber flywheel rotating at speeds up to 65,000 rpm within a vacuum-sealed housing and supported by precision bearings [8]. A Hydraulic Launch Assist uses a pump/motor to convert the kinetic energy to pressurize fluid for refuse trucks and buses with frequent start-stop operation [9]. A mechanical RBLA system using strain energy that is stored and released using a pair of clutches was proposed by Hoppie [10]. Nieman et. al, developed a more compact, spring-based, RBLA mechanism that consisted of gears, clutches, and a ratchet and pawl arrangement [11].

Elastic strain (springs) has been used as a source of energy storage for lifting applications such as garage doors, overhead ladders and automotive hoods. Springs are not commonly considered as a viable option for widespread, high energy storage. At approximately 0.3 kJ/kg (100 ft-lb/lb) [12], the specific energy density of a steel spring is much less than the 100 kJ/kg (35,000 ft-lb/lb) for batteries used in hybrids [13]. Despite having a low energy density, however, springs are able to rapidly release their stored energy. This "power density" can make a spring an attractive alternative for launch assist applications. Additionally, springs are an environmentally friendly alternative to batteries and their well-known design methods provide durable and reliable behavior. However, elastic springs, such as rubber,

have much a larger energy density of 12 kJ/kg (4,000 ft-lb/lb)[12], but further research studies must be completed to assess the fatigue life of these materials at high strain. Ongoing research by Hill et al. involves constructing springs from carbon nanotubes, having an energy density of 800 kJ/kg (270,000 ft-lb/lb) greatly exceeding the capacity of batteries [14]. Commercialization of this technology greatly enhances the attractiveness of an elastically-based RBLA system.

This paper explores an alternative to Hoppie's and Nieman's mechanical RBLA systems, which allow conventional vehicles to benefit from regenerative braking. While both concepts have merit, they require precisely sequenced control and have the potential to reflect unwanted shock and vibrations through the vehicle. Additionally, Nieman's concept contains an extension spring that may pose a safety risk. The alternative concept presented in this paper involves an open differential and variable transmission that can smoothly adjust the rate of braking and launching. Additionally, a torsional spring is used to more safely store energy. The remainder of the paper is organized as follows. Section 2 describes the general RBLA concept. The equations governing the design details and vehicle response are developed in Section 3. Section 4 presents a dynamic simulation performed to confirm the design equations. To have the greatest effect on a vehicle, an optimization to determine ideal design values is presented in Section 5. The development of a benchtop prototype to validate this RBLA concept is described in Section 6.

2. DESCRIPTION OF CONCEPT

The mechanical RBLA concept is intended to be attached to the non-driven axle of a conventional vehicle. It operates in three modes: charge or regenerative braking (RB), discharge or launch assist (LA), and idle. When the RBLA is in charging mode, the spring deforms as it stores energy. In discharge mode, the spring deformation is relieved as stored energy is released. The elastic storage medium can be configured as an extension, torsion or bending element. All of these strain-based storage configurations exhibit a deformation and relaxation cycle that involves a reversal of directions. Since the RBLA is intended to function only when the vehicle is moving, the mechanism must account for these reversals as the axle rotates in a single direction. The idle mode retains any charge in the spring and disengages the RBLA, allowing the vehicle to function as normal.

A sketch of the mechanical RBLA concept is shown in Fig. 1.

The four major components of the RBLA are identified below.

- I. A gear drive will transfer motion from the axle to Countershaft A at a fixed ratio. Being external gears, the axle and Countershaft A will rotate in opposite directions.
- II. A transmission will transfer motion from the axle to Countershaft B at a variable ratio and has the capacity to vary both above and below the ratio of the gear drive. The transmission is configured such that the axle and Countershaft B will rotate in the same direction.
- III. An open differential is configured such that the rotation of the carrier is achieved by combining the motion of Countershaft A and Countershaft B. Since Countershaft A and B rotate in

different directions, the differential carrier rotation will depend on the difference between the two countershafts. Differentials are commonly used in automotive applications and proven to be both robust and compact.

- IV. The energy storage spring is attached through an energy storage gear pair to the carrier of a differential. As stated, various types of strain-based storage devices could be implemented. In the proposed design of Fig. 1, a torsional spring element is used because less volume is required when the spring is storing energy. Alternatively, an extension band stores energy more efficiently because the material within the spring is at the same stress level. In that case, the spring could be attached to a strap the winds onto a spool attached to the differential carrier.

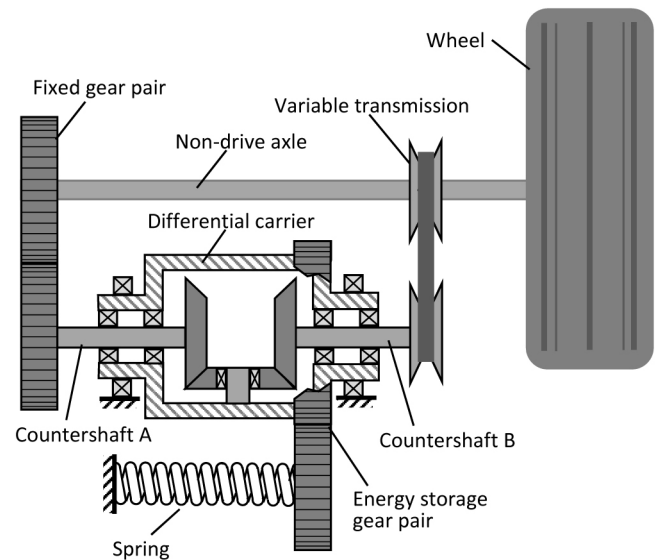


Figure 1. Concept sketch of the RBLA device.

When the variable transmission is adjusted to a ratio equal to the gear drive, Countershaft B rotates at exactly the opposite angular velocity as Countershaft A. The net rotation is zero resulting in no motion of the carrier, and subsequently, the spring. The differential is a critical component of the design, noting that this stasis may be produced even while the axle shaft is rotating. That is, with the RBLA in this neutral position, the spring neither stores nor releases energy and no additional load is exerted onto the axle.

Moving the ratio of the transmission from the gear ratio causes Countershaft B to rotate with an angular velocity that is not equal and opposite to Countershaft A, which will cause the carrier to rotate. The motion of the carrier can either increase or relieve the deformation of the spring. In the case of an increased deformation, the energy to produce this increase is taken from the axle (slowing the vehicle). As the deformation is relieved, the energy is returned to the axle (accelerating the vehicle). Thus, the concept may be charged from, discharged to, or produce no net effect on a axle that (primarily) rotates in a single direction.

The initial RBLA concept is designed to be installed onto the non-driven shaft of a two-wheel drive vehicle. This will lessen the necessary controls of the system. Sensors must be used to monitor the level of spring charge. While charging or discharging, the spring-

deformation will be continually changing, thus the torque affecting the speed of the vehicle will also change. Hence, the RBLA is not designed to be the sole means to propel or stop the vehicle. For example, during launch assist the spring is releasing torque to the non-drive wheels. If the driver desires a higher acceleration, pressing the gas pedal harder will apply torque from the engine to the drive wheels. With differing amounts of torque applied to the wheels, the drive wheels will dictate the speed the car moves, while the RBLA will lessen the torque required. Regenerative braking is a similar scenario, where the brakes aid the spring. The peak acceleration of the RB and LA cycles are limited to standards of comfort, thus it is assumed that the RBLA will aid required accelerations, not define them. Each mode will have the least effect on vehicle speed when the spring is closest to the discharged state, and the greatest effect when the spring is closest to fully charged.

3. DESIGN EQUATIONS

In this section, the equations used to determine appropriate design parameters are formulated.

Vehicle Response to the RBLA

A free body diagram of an automobile of mass m_c being propelled by the RBLA is shown in Fig. 2. The principal vehicle forces include drag F_D , the weight $W = m_c g$, the normal forces on the tires N , and the thrust F_T from the launch assist. The vehicle motion coordinate x_c is also defined in Fig. 2 with velocity $\dot{x}_c$ and acceleration $\ddot{x}_c$. Note that F_T can be either with or against motion $\dot{x}_c$, depending on whether the mechanism is in LA or RB mode.

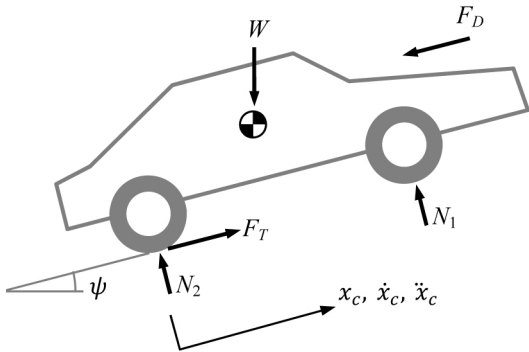


Figure 2. Free body diagram of the vehicle being propelled by the RBLA

Summing the forces along the direction of motion,

$$F_T - F_D - W \sin \psi = m_c \ddot{x}_c. \quad (1)$$

The drag force of the vehicle is dependent on the reference frontal area S , the coefficient of drag C_D , the air density ρ_a and the speed of the air with respect to the vehicle, which is assumed to be the speed of the vehicle $\dot{x}_c$,

$$F_D = \frac{1}{2} C_D S \rho_a \dot{x}_c^2. \quad (2)$$

The torsional energy storage spring has a constant of k_θ and has an angular deflection of θ_s . With a tire radius of r_w , the rotation of the axle is $\theta_w = x_c / r_w$. The angular rotation of Countershaft A, Countershaft B, and the differential carrier are θ_A , θ_B , and θ_D , respectively. The differential carrier exhibits motion that is dictated by $\theta_D = (\theta_A - \theta_B) / 2$. The RBLA has velocity ratios between Countershaft A and the axle of $R_A = \theta_A / \theta_w$, between Countershaft B and the axle of $R_B = \theta_B / \theta_w$, and between the differential carrier and the energy storage spring of $R_s = \theta_s / \theta_D$. Note that the ratio for the variable transmission will be changed for brake mode $R_{B_B} > R_A$ and launch mode $R_{B_L} < R_A$. With an initial angular deflection of θ_{s_0} , these ratios form a relationship between the displacement of the car and the spring deflection as

$$x_c = \frac{2r_w (\theta_{s_0} - \theta_s)}{R_s (R_A - R_B)}. \quad (3)$$

A spring torque of $k_\theta \theta_s$ produces a torque on the differential carrier of $R_s k_\theta \theta_s$. Transferring that torque through the differential and to the wheel axle gives $R_s (R_A - R_B) k_\theta \theta_s$. Summing torques on the axle,

$$\frac{1}{2} R_s (R_A - R_B) k_\theta \theta_s - F_T r_w = J \ddot{\theta}_w, \quad (4)$$

where $\ddot{\theta}_w$ is the acceleration of the axle and J is the effective rotational inertia of the RBLA system along with the wheels. Note that $\ddot{\theta}_w = \ddot{x}_c / r_w$. Substituting into Eq. (4), the thrust force produced by the spring is

$$F_T = \frac{R_s (R_A - R_B) k_\theta \theta_s}{2r_w} - \frac{J}{r_w^2} \ddot{x}_c. \quad (5)$$

Substituting Eqs. (5) and (2) into Eq. (1),

$$\frac{R_s (R_A - R_B) k_\theta \theta_s}{2r_w} - \frac{J}{r_w^2} \ddot{x}_c - \frac{C_D S \rho_a}{2} \dot{x}_c^2 - W \sin \psi = m_c \ddot{x}_c. \quad (6)$$

Further substitution of Eq. (3) into Eq. (6) produces the equation of motion for a vehicle launching or braking, when the spring has an initial stretch of θ_{s_0} ,