Flywheel Energy Storage and Release via Continuously Variable Transmissions

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Abstract – A prototype mechanical energy storage system was designed and created using a flywheel and continuously variable transmissions (CVTs) with the objective of determining the feasibility and complications associated with using such a system for regenerative braking. Flywheels have been used for centuries as energy storage devices; one that provides a good alternative to electrochemical energy storage systems when storing mechanical energy. An automotive flywheel was used to store input rotational kinetic energy. CVTs allow for infinite gear ratios within a maximum and minimum range, allowing for smooth energy transfer. Two bicycle grade NuVinci 171B CVTs were employed with the intent of gradually introducing and removing energy from the rotating flywheel. Current testing results indicate that the flywheel must be balanced with a high degree of accuracy, which has proven difficult. Very low rotational speed input/output is obtainable but the smooth introduction and removal of energy is not yet demonstrable.

Keywords: flywheel, energy, cvt, storage

BACKGROUND

Using flywheels for the purpose of storing and releasing energy is not a new application. In fact a flywheel's sole purpose is almost invariably to store and release rotational kinetic energy. When used in an internal combustion engine, flywheels increase the moment of inertia of the crankshaft assembly, smoothing out the engine's power pulses and therefore its rotation. [Woodford, 7] Flywheels have also been used in electrical generators or uninterruptable power supplies. In such a system, a flywheel is maintained at a certain rotational speed, replacing batteries or fuel tanks as an energy storage device. When the generator or uninterruptable power supply system is required, the flywheel is then used to spin an electrical generator and produce electricity. [Lombardi, 3]

Continuously Variable Transmissions (CVTs) are power transmission systems that allow the fluid changing of gear ratios. A Continuously Variable Planetary CVT employs two rings, mechanically coupled by a rotating set of balls, see Figure 1. [Fallbrook Technologies, 5] The direction of the balls' axes of rotation is variable. This allows the effective circumference of the balls as seen by each ring to be variable, effectively changing the gear ratio. The rotating parts of the transmission are bathed in a normally liquid lubricant that, when compressed between the surfaces of the balls and rings, becomes solid, allowing power transfer. [Fallbrook Technologies, 5]

Regenerative braking is a process where a vehicle's kinetic translational energy is stored during braking, and then released during acceleration. Regenerative braking systems never replace conventional brakes; they are used to augment them. Many systems of this type currently in production use electromechanical means of braking the automobile. [Wikipedia, 6] There can be one or several drive motors that are used to charge a battery or capacitor during braking. When the vehicle accelerates, the charged batteries or capacitors are used to power the drive motors. [Autoshop101, 1]

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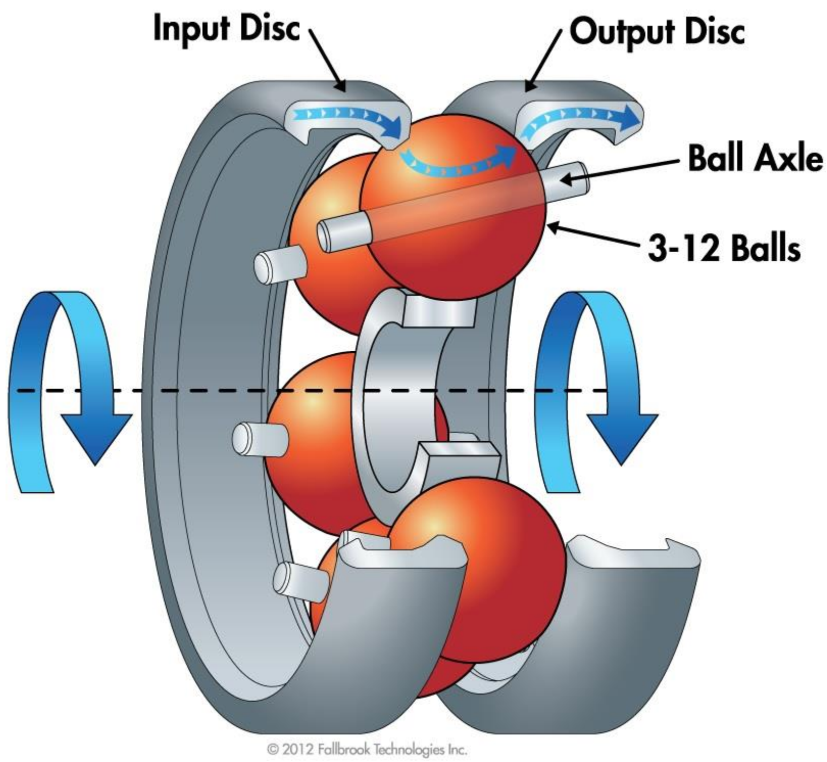

Figure 1: NuVinci CVP Basics of Operation [Fallbrook Technologies, 5]

There are several drawbacks to the current system of electrical regenerative braking. Current battery and capacitor technology has a limited charge rate. During braking, the rate at which energy must be removed is proportional to the desired deceleration of the vehicle. Most batteries and capacitors cannot handle the in-rush of current associated with rapid braking at high speeds. [Wikipedia, 6] This prevents them from efficiently storing all of the braking energy. The excess energy is often wasted as heat, either through traditional mechanical friction braking systems or through resistive electrical loads. [Autoshop101, 1] Also, there are inherent inefficiencies when changing from one type of energy to another. Most electrical regenerative braking systems convert the kinetic energy of the automobile into electrical energy by the drive motors, which is then converted into chemical energy by charging onboard batteries. Finally, most current and older vehicles do not employ electrical drive or storage systems, making this system impractical for use on these vehicles.

Purely Mechanical Alternative

A possible alternative to the electrical regenerative braking systems would be a mechanical system using a flywheel to store translational kinetic energy as rotational kinetic energy. Such a system would be best suited to trucks and larger vehicles, wherein the flywheel could be mounted beneath a bed or rear deck. The flywheel could be coupled to the driveshaft or drive axle using clutches and a CVT. The CVT would allow fluid changing of the gear ratio between the flywheel and drive train, permitting smooth braking action as the flywheel spins up and the vehicle slows down. This procedure could operate in reverse to remove the stored energy from the flywheel, smoothly accelerating the vehicle. Electrical control systems would need to be employed to comfortably augment the power supplied by the engine during acceleration, and provide smooth, controlled deceleration during braking.

Initial Feasibility Calculations

Before beginning further investigation into the complexities of a regenerative braking system of the mechanical type, the basic feasibility of storing vehicle energy in a flywheel was addressed. In order for this system to be practical, a reasonable amount of the vehicle's energy must be able to be stored in a flywheel of equally reasonable dimensions. For the purposes of this analysis, pure conversion from translational kinetic to rotational kinetic energy was considered, and friction was neglected. As friction would only remove energy, the actual required flywheel size will be less than that predicted which is acceptable. The translational kinetic energy of a vehicle is equal to one half the product of the mass of the vehicle, m_v, and the vehicle's speed, V. Rotational kinetic energy of such a simple flywheel is equal to one half the product of the mass moment of inertia of the flywheel, I, and its angular velocity, ω.

By setting the two equations for kinetic energy equal to each other, and using reasonable values for the vehicle's *mass*, the flywheel's *mass moment of inertia*, and the vehicle's *speed*, a required *angular speed* of the flywheel can be determined. The flywheel was modeled as a simple solid cylinder. The *mass moment of inertia* for such a flywheel is equal to half the product of the *mass* of the cylindrical flywheel, m_c, and the square of its *radius, r*. In practice, the mass of the flywheel would be distributed as far as possible from the flywheel's center, raising the moment of inertia and therefore the amount of energy stored per revolution.

$$K.E. = \frac{1}{2} m_V V^2$$ Translational Kinetic Energy

$$K.E. = \frac{1}{2} I \omega^2$$ Rotational Kinetic Energy

$$I = \frac{m_c r^2}{2}$$ Mass Moment of Inertia for Solid Cylinder

The calculations were performed to convert all of the kinetic energy of a typical pickup truck, weighing 5,000 lbs, into rotational energy of a flywheel 3ft in diameter and weighing 300 lbs. For such a truck braking from 50 mph to a stop, the flywheel would have to turn roughly 2,700 rpm, which is a reasonable speed for automotive grade flywheels. Thus a reasonably sized flywheel could store enough of a truck's kinetic energy to make it feasible, even for such large reductions in speed.

Scale-Model Design

The purpose of this project was to design and construct a small-scale working model of a flywheel energy storage system, using CVTs to introduce and remove power from the system. The complexities of constructing such a system and its feasibility as applied to a regenerative braking application were explored.

This system was designed to use a flywheel from an over-the-road semi truck engine as the energy storage device. An appropriate mass for the scale of this project would be 40 kg to 50 kg. Such a flywheel will be balanced for rotational speeds up to 3,000 rpm. Due to safety considerations, the rotational speed of the flywheel will be limited to 800 rpm.

The CVTs employed for power transfer are NuVinci 171B CVPs (Continuously Variable Planetary, the ball-ring variety of CVT), part of Fallbrook Technology's Developer Kits, Figure 2. [Fallbrook, 4] These CVTs are built for bicycles or light electric vehicles (LEVs) and their maximum power, 5 hp, and rotational speed, 1,000 rpm, specifications meet the project requirements. The main limitation of these CVTs as applied to this application is due to their internal freewheeling systems. As they are meant for bicycles and LEVs, these CVTs only transmit torque in one direction and therefore one CVT cannot be used for both power input and output. Thus, two of these CVTs were employed, one mounted to each side of the flywheel; one for power input, the other for power output. The Developer Kit includes a microcontroller run electrical shifting system which allows the transmissions to be shifted in response to various sensors, such as a gas and brake pedal.

The flywheel-CVTs assembly was mounted on a steel frame to provide a safe, sturdy support structure. The CVTs themselves are not robust enough to support the flywheel on their own, so much of the flywheel's weight rests on two 4" rollers beneath it.

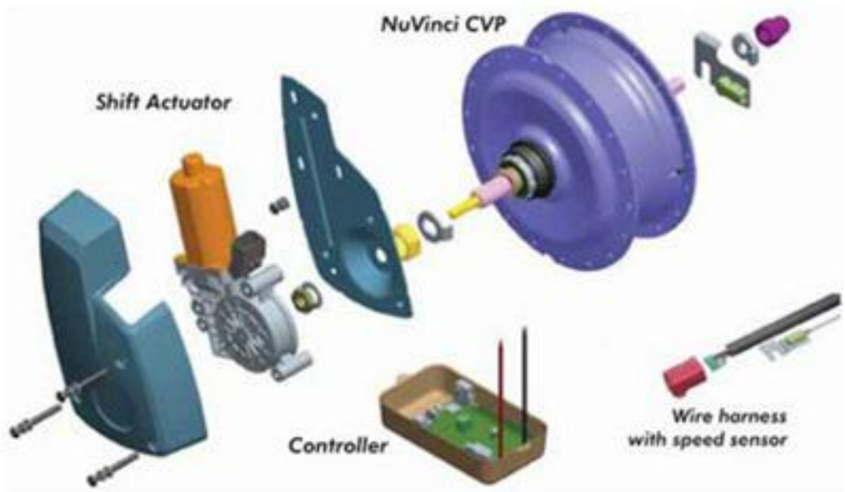

Figure 2: NuVinci 171B Developer's Kit [Fallbrook Technologies, 4]

Testing of the system was accomplished using a variable speed electric motor as the drive axle. In order to prove the basic concept, it needs to be possible to smoothly introduce and remove power from the system. The motor should be able to smoothly spin up the flywheel at various speeds. Once the flywheel is spinning, power will be cut to the drive motor and the energy in the flywheel will be used to keep the motor spinning at a set speed until the flywheel speed drops below the minimum value allowed by the CVTs.

SCALE-MODEL CONSTRUCTION AND TESTING

A suitable flywheel was acquired from a Cummins IBL diesel engine. The energy storage capacity of the automotive flywheel was found similarly to the initial feasibility calculation. The mass moment of inertia of the flywheel was greater than was originally calculated due to the flywheel's mass being distributed unevenly, with greater mass farther from the axis of rotation. This leads to a slightly understated energy capacity. The mass of the flywheel was found to be 41.5 kg, which gives a moment of inertia of 4.337 kg m2. The maximum rotational kinetic energy that can be stored in this rotating flywheel is then calculated as 10.9 kJ at 800 rpm.

Two NuVinci Developer Kits were acquired. The CVTs have been mounted to the flywheel using custom machined adapter plates. The flywheel to CTV spacing was adjusted to give a minimum axial run-out of 0.1". A steel frame was constructed and power and load testing motors were mounted to it. The flywheel-CVT system was mounted in the frame and supported by the rollers.

A Krause & Becker Model 69856 Dual Speed Mixer was used to provide power to the system. The mixer uses an AC motor and incorporates a two speed gear reduction box, for maximum rotational speeds at the output shaft of 470 rpm and 775 rpm. [Harbor Freight, 2] A Variac allows for the output power and speed of the motor to be varied, providing a variable input. A separate AC motor, salvaged from a Black & Decker electric chainsaw was used as an output load. The power and load testing motors have been connected mechanically to the CVTs by bicycle grade chain and sprockets. See Figure 3 for the constructed test setup.

Low speed tests runs, 50-70 flywheel rpm, have resulted in significant vibration in the flywheel-CVTs assembly. During the test runs the flywheel-CVTs assembly would commonly exhibit 1" of radial run-out, up to 1.5" of run-out. It is believed that this is due to an incorrect alignment between the flywheel and the CVTs, as each is independently rated to 3,000 rpm and 1,000 rpm, respectively. Improving the alignment between these three parts beyond 0.1" has proven difficult, as each part does not mount flush with its corresponding adapter plate; rather they are attached with many sections of threaded rod. Very low rotational speed input/output is obtainable but the smooth introduction and removal of energy is not yet quantifiable.

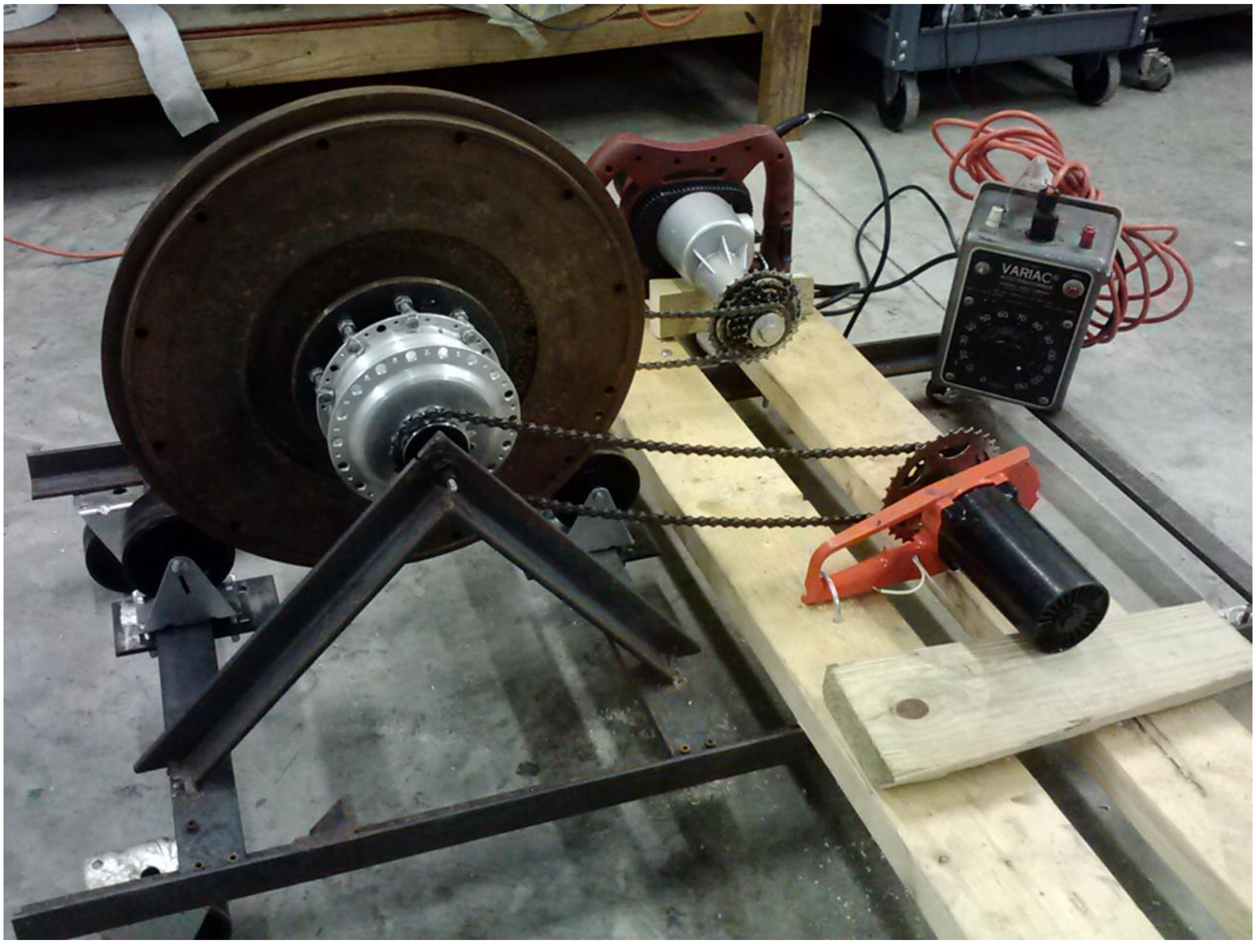

Figure 3: Flywheel-CVT Test Setup

RECOMMENDATIONS FOR FUTURE WORK

It is believed that costly machined spacers between each CVT and the flywheel are required to align the flywheel and transmissions with the degree of precision that will enable for higher testing speeds capable of utilizing the gear range of the NuVinci CVTs. Additionally, the Krause & Becker Model 69856 Dual Speed Mixer is slightly under powered for this application as the motor requires manual assistance to begin spinning the flywheel from rest. It is believed that a more powerful motor would be required to spin the flywheel much faster than the 50-70 rpm of the low speed test run.

Once the system is aligned to a sufficient degree to allow it to rotate at speeds within the CVTs gear range, the electronic shifting system needs to be mounted and interfaced to the Arduino Uno microcontroller. The Arduino will also need input and output speed data as well as sensors that would simulate a gas and brake pedal to effectively model an automotive regenerative braking system.

If the flywheel-CVT system balancing issues can be overcome with the current setup and the testing results are promising, the next step is to make this system more compact and contained. Electric clutches also need to be introduced so the constant connection to the flywheel doesn't limit the driving axle. This would allow the flywheel system to be connected to and disconnected from the drive axle while one is at rest and the other rotating, as in a typical automotive situation. Once it is enclosed in a stable fashion, it can be installed on a small vehicle, such as a go-kart. The electronic control systems would have to be adapted to monitor real throttle and brake pedal position as well as drive axle and flywheel rotational. These inputs would be used to smoothly introduce and remove energy from the flywheel system. If this flywheel were to be mounted on a typical go-kart it could store the energy required to decelerate from 30 mph to near rest.

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