Analysis of an Electromechanical Flywheel for Use as a Dedicated High-Power Device in a Hybrid Electric Vehicle

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Abstract—**Hybrid vehicles are becoming increasingly popular as the world become more environmentally conscious. The efficiency of hybrid vehicles is limited by the ability of their electrochemical batteries to absorb large regenerative braking currents. Any energy over what the battery can safely absorb is dissipated through the friction brakes of the vehicle. This work will investigate the use of a dedicated high-power device, specifically an electro-mechanical flywheel, to absorb the excess energy and return it to the vehicle batteries. Both modelling and experimental approaches are utilized to analyze the increase efficiency potential, as well as the ability of the electromechanical flywheel to absorb excess braking energy.**

Index Terms—**Batteries, electromechanical devices, flywheel, hybrid vehicles**

I. Introduction

Hybrid electric vehicles are claimed to be better for the environment than traditional vehicles. However, if the batteries are mistreated, and their lifetimes shortened, significant negative environmental consequences can be observed [1]-[3]. Extending the life of the battery can keep environmental impacts to a minimum, decrease the amount of lithium required for new batteries, and reduce the rate of batteries which need to be recycled. The objective of this work is to investigate how a dedicated high-power device can be incorporated into an electrified vehicle to extend battery life. The secondary objective of this paper is to determine if adding a dedicated high-power device can increase the efficiency of a hybrid vehicle.

It has been shown that high charge and discharge rates (rates over 1C) can lead to degradation of lithium ion batteries [4], [5]. The reason for this may be the increase in battery temperature associated with high charge and discharge rates [6], [7]. The need for a hybrid component between a battery and a high-power device, which may lessen the demands of the battery, has been demonstrated [8], [9]. Hybrid batteries with properties of capacitors and batteries are being developed but are not yet on the market [10], [11]. This paper will investigate the energy flow of a hybrid vehicle incorporating a dedicated high-power device. The device used in this study is an electromechanical flywheel which is located in the INSTAR lab at the University of California, Berkeley [12]. Flywheels have been shown to be an acceptable device for high power applications in a hybrid type vehicle, and recent papers demonstrate that they may be less expensive than other similar type technologies [13]-[17]. A computational model based on laboratory experiments is created to investigate the energy flow of a vehicle over an urban driving cycle. Results showing that battery charging currents can be reduced will indicate that battery lifetime has been increased.

II. Model Parameters

A computational model was constructed in MATLAB to simulate a vehicle driving over a specified driving cycle and determine the impacts a dedicated high-power storage device can have on the vehicle performance. The goal of the model was to simulate a typical driving event for an American person living in a suburban community who needs to travel into an urban environment for work or other activity. The car chosen for the model is the Toyota Prius having a mass of 1380 kg [18], a drag coefficient of 0.26, and a frontal area of 2.22 m^2 [19]. A driveline efficiency of 89% was assumed for the vehicle and is taken from the rolling friction of the tires on the ground [20]. A traction motor efficiency of 100% was assumed for the study.

The battery pack of the vehicle was set to a size consistent with that of a common commercially available hybrid vehicle, in this case the Toyota Prius. The 2017 Toyota Prius has a nominal battery voltage of 207.2 V, and a battery capacity of 3.6 amp hours (0.75 kWh) [21]. The simulated flywheel represents the electromechanical flywheel deployed in the lab. The flywheel motor efficiency was set to 90%, and the parasitic power loss of the flywheel was set to 200W, which is representative of the actual losses seen with the flywheel.

The driving profile selected for the model is the EPA Urban Dynamometer Driving Schedule (UDDS) and was placed on a perfectly flat plane. The driving profile consists of many starts and stops, with brief periods of acceleration (Fig. 1). The driving cycle represents a typical driving cycle for an urban or suburban driver and

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has three main segments. The first segment is from 0 to 150 seconds and represents driving in a suburban area without many stops. The second segment is from 150 to 350 seconds and represents travel on an American highway or main road, where the vehicle speed approaches 90 kph (55 mph). The remainder of the driving cycle represents urban driving with many starts and stops in quick succession. The length of the UDDS is 12.07 km (7.5 miles).

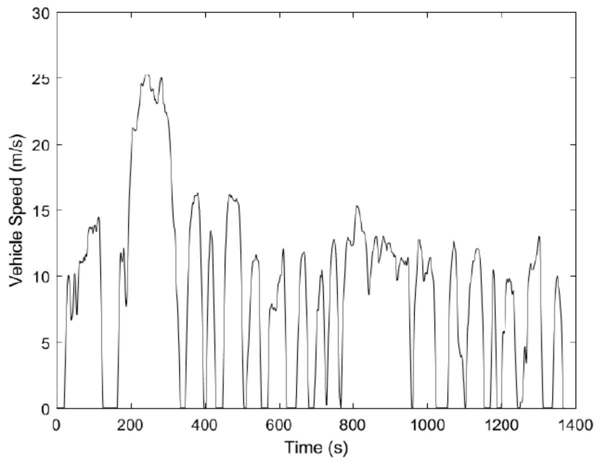


Fig. 1. UDDS driving profile speed v. time.

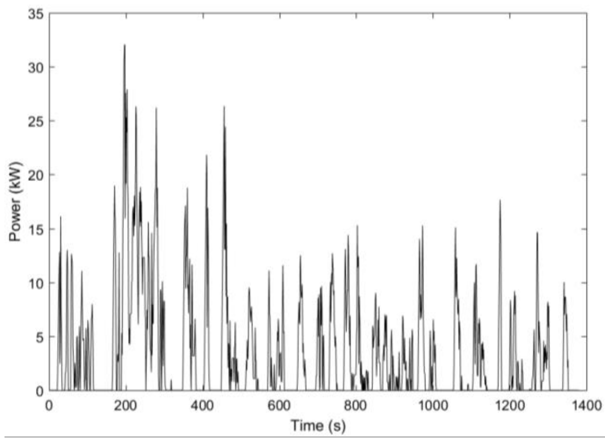


Fig. 2. UDDS driving profile power requirement v. time

The power profile necessary to complete the driving cycle consists of many abrupt spikes in power. The spikes last for only the time duration of the acceleration events of the vehicle, and a consistent power demand is not observed (Fig. 2). The peak power required for acceleration of the vehicle is 32.5 kW (43.6 HP), well over the 1C level of the battery (0.75 kW), requiring the internal combustion engine (ICE) be used to protect the battery from damaging currents. The average power required is only 3.044 (4.08 HP) and the total energy used for a hybrid vehicle with a 1C regeneration limit is 4,169.9 kJ. The goal of the modeling is to show that recapturing additional energy with an electromechanical flywheel can reduce the amount of energy used and power output required. Model algorithms will send power to the flywheel during regenerative braking, then deplete the energy to charge the batteries, or accelerate the vehicle.

III. Modeling Results

A. Regenerative Braking Modelling

The control scheme implemented in the model is aimed at maximizing energy efficiency. In the control strategy, any regenerative braking current in excess of 1C were sent to the flywheel, and when the regenerative braking current dropped below 1C, the flywheel was discharged to the batteries at 1C. Any power left in the flywheel during an acceleration event was used to augment a battery and ICE combination of 3 kW. 3 kW was selected because it is slightly less than the average power output required for a traditional hybrid vehicle to complete the driving cycle. 3 kW equates to a 1C battery discharge plus a 2.25 kW (about 3 HP) ICE generator.

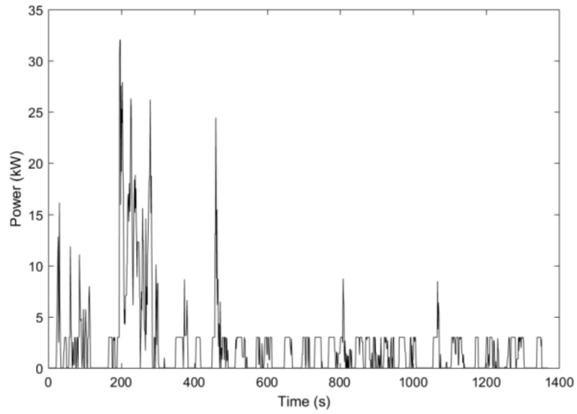


Fig. 3. Power draw from the battery and ICE over the UDDS with the flywheel algorithm activated

Using this strategy, the amount of energy needed to propel the vehicle through the driving cycle reduced from 4,169.9 kJ to 2,487.0 kJ, a 40.36% reduction over a traditional hybrid vehicle capturing only 1C of regenerative braking currents. Using a 30% engine thermal efficiency, and a 34.2 MJ/l energy density for gasoline this would equate to an improvement in modeled fuel economy from 29.7 kpl for a traditional hybrid to 49.8 kpl for the modeled flywheel integrated hybrid. Peak power was not reduced over the cycle, but there are observable reductions in the power peaks from the battery and ICE in other portions of the driving cycle (Fig. 3). A summary of the energy and power levels needed to complete the UDDS for a conventional vehicle, a traditional hybrid vehicle, and a vehicle utilizing a flywheel can be seen in Table I.

TABLE I: RESULTS OF REGENERATIVE BRAKING MODELING

Vehicle configuration	Energy used (kJ)	Average power output from battery/ICE (kW)	Estimated fuel economy (km/l) (30% thermal eff.)
Conventional vehicle	4,649.1	3.396	26.6
Traditional hybrid with 1C regeneration limit	4,169.9	3.044	29.7
Maximum efficiency with flywheel and 1C battery limit, 2.25 kW ICE	2,487.0	1.815	49.8
Power peak minimization with flywheel and 1C battery limit, 2.25 kW ICE	2,965.5	2.165	41.76

Another control strategy was implemented in an attempt to reduce the power peaks not reduced with the previous algorithm. In this algorithm, all of the regenerative braking energy was stored in the flywheel, and none was sent to the batteries. This strategy would leave the maximum amount of energy in the flywheel to be used to offset the power requirement from the ICE/battery combination. This strategy showed little improvement over the previous strategy, and the only additional power peaks which were reduced were at 800 and 1100 seconds. Energy is stored in the flywheel for longer periods using this strategy. Because of this the energy requirement to complete the driving cycle increased due to the flywheel's parasitic losses (Table I). The slight reduction in power peaks from the battery/ICE is likely offset by the larger usage of energy, and it is better to remove energy from the flywheel as soon as possible, rather than store it for long periods of time to aid in acceleration.

B. Pre-Charge Modelling

Regenerative braking energy alone did not provide sufficient energy to reduce all of the peaks in the power demand from the ICE and battery combination. More energy must be stored in the flywheel than can be provided from the regenerative braking alone. One strategy is to use the ICE and battery to pre-charge the flywheel with energy before an acceleration event. The strategy implemented for modelling was to use an ICE and battery output of 3 kW to pre-charge the flywheel. 3 kW was chosen because it represents the average power required to complete the driving cycle and was already used for the previous modelling exercises. The flywheel was pre-charged with energy whenever the vehicle was at a stop, because this could indicate that an acceleration event is about to occur.

The results of the modelling exercise show that the pre-charging was successful in eliminating all of the peaks in power from the ICE and battery combination during the stop and go urban portion of the driving profile (Fig. 4). The pre-charging strategy was also successful in reducing the peak power required from the ICE and battery from 32.1 kW to 27.9 kW.

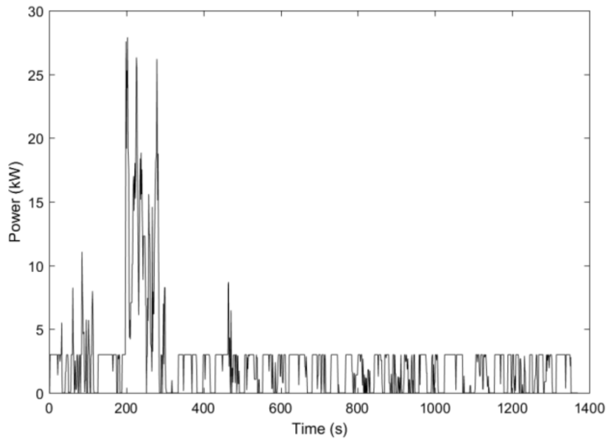


Fig. 4. Power draw from the battery and ICE over the UDDS with the flywheel when a flywheel pre-charge of 3kW is used

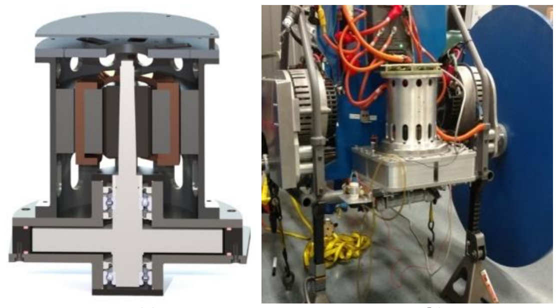
It is worth noting that more energy than required was stored in the flywheel during the stop-and-go urban portion of the driving profile. This energy could be used for a large acceleration event similar to the one at the 200s mark. However, if a large acceleration event does not come, then more energy the necessary will be lost due to parasitic losses of the flywheel. Smart control algorithms would be needed to determine how much energy must be stored in the flywheel to achieve optimal energy usage.

IV. Experimental Validation

A. Experimental Setup

Demonstration that a flywheel can be used to absorb excessive currents and lower battery demands was completed in a laboratory setting. Laboratory experiments focused on both the magnitude of regenerative braking peaks, as well as the energy efficiency of the system. The laboratory testing apparatus is an electrified go-kart with two 12kW DC brushless motors. The kart uses two 80V LiFePO4 batteries in parallel for a combined capacity of 40Ah. The dedicated high-power device used on the kart is an electromechanical flywheel having a maximum energy storage capacity of 112.9 kJ (Fig. 5).

Control of the kart is accomplished though code implemented in National Instruments LabVIEW software. The supervisory controller is a National Instruments cRIO-9076 equipped with a 400 MHz real time processor and Spartan-6 FPGA. Control of the traction motors and flywheel is accomplished through CAN communication to the dedicated Sevcon Gen4 motor controllers.



(a) (b)

Fig. 5. Electromechanical flywheel: (a) Cutaway section view of the flywheel used for experimental testing and modelling and (b) the experimental platform showing the flywheel and the large steel disc which simulate the momentum of the moving cart.

The electromechanical flywheel throttle was controlled with an open loop control algorithm. The algorithm was designed to match the flywheel current absorption with the current generated by the vehicle traction motors. The algorithm was designed and tested by previous members of the INSTAR lab and is reproduced below [6]. The values for the coefficients are A=0.4, B=0.4, C= −0.12, D=0.4, E=2.7, F=2.7.

$$\text{Flywheel throttle signal} = F\left(\frac{A(T_B * \omega_V) - BT_B + C\omega_V}{D\omega_f + E}\right)$$

The driving profile for the tests was similar to the UDDS used in the modelling. Because of limitations in the laboratory, the magnitude of the driving profile had to be reduced by an order of magnitude to ensure safety of the lab members. Though the magnitude of the driving profile was decreased, it followed the start-stop nature of the UDDS. The driving profile was first executed regenerating all energy through the batteries. The flywheel was then activated with the goal of keeping all battery charging peaks below 10 amps.

B. Regenerative Braking Experimental Results

The baseline testing with no flywheel energy recovery revealed 11 battery charging peaks over 10 amps, with a maximum battery charging peak of 25 amps. The desired maximum battery charging current for this work is 10 amps. Through use of the flywheel and the open loop controller, the number of battery charging peaks over 10 amps was reduced to only 1, with a maximum of 13 amps. This is a positive result of activating the flywheel, by reducing the charging load on the battery, the batteries can be protected while still recapturing regenerative braking energy.

Once the energy is placed in the flywheel, it must be returned to either the battery, or to the traction motors. If the energy placed into the flywheel is wasted, then the flywheel is not serving any purpose, as excess regenerative braking energy is already dissipated through the friction brakes of a hybrid vehicle. To remove the energy from the flywheel, a constant brake signal was applied to the flywheel when no flywheel throttle signal was present. Fig. 6 shows the round trip current flow of the flywheel. Positive current indicates power sent to the flywheel from the open loop control algorithm, and negative currents indicate current removed from the flywheel and delivered to the electrochemical batteries.

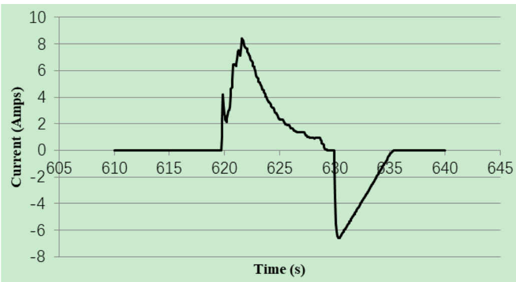


Fig. 6. Flywheel round trip current profile

TABLE II: EXPERIMENTAL RESULTS

Situation	Total energy use (kJ)	Total traction motor energy (kJ)	Normalized energy usage (battery energy/motor energy)	Energy efficiency (motor energy/battery energy
Full Regeneration with no restrictions	604.232	369.835	1.6338	0.6121
Maximum 10 amp regeneration	611.134	369.835	1.6525	0.6052
Maximum 5 amp regeneration	627.691	369.835	1.6972	0.5892
No regeneration	667.743	369.835	1.8055	0.5539
Flywheel test	624.294	367.773	1.6975	0.5891

Table II shows the energy usage of the testing vehicle for 5 situations: full regeneration with no restrictions on regeneration current returned to the battery, simulated energy usage if the maximum current sent to the batteries were 10 amps or 5 amps, a case where there was no regeneration at all (conventional vehicle), and the case with the flywheel activated. The trial with the flywheel activated achieved an energy usage in between that of the 10 amp and 5 amp regeneration limit situations.

C. Pre-Charging Experimental Results

Experiments were conducted to investigate using a pre-charging strategy to lower the discharge current out of the test vehicle batteries to accelerate the vehicle. The purpose of the experiment is to limit the discharge current out of the batteries to 50 amps during an acceleration event. To conduct the experiment, an acceleration event was selected from the UDDS driving profile (Fig. 7). Prior to the acceleration event, the flywheel was sent a constant throttle signal to pre-charge the flywheel with energy from the batteries. This energy was then depleted from the flywheel during the acceleration event to reduce the magnitude of power required from the batteries during the acceleration.

The algorithm used to calculate the braking signal sent to the flywheel motor controller to offset the power required from the vehicle battery is similar to the algorithm used to calculate flywheel throttle signal in the regenerative braking experiments. The algorithm is reproduced below, and the coefficients are A=0.4, B=0.4, C= −0.12, D=0.4, E= −2.7, F=50.

$$\text{Flywheel brake signal} = F\left(\frac{A(T_{\text{Accel}} * \omega_{\text{Vehicle}}) - BT_{\text{Accel}} + C\omega_{\text{Vehicle}}}{D * \omega_{\text{flywheel}} + E}\right)$$

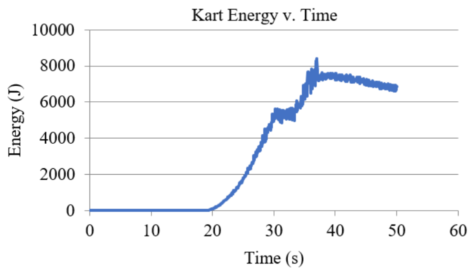


Fig. 7. Acceleration event for pre-charge testing

During testing it was found that the current to the traction motors had two peaks, one during the beginning of the acceleration event, from 17 seconds to 30 seconds, and another from 33 seconds to 38 seconds (Fig. 8). To accommodate this two-peak acceleration demand, the flywheel was also pre-charged in between the acceleration peaks in the time period between 30 seconds and 33 seconds.

Traction motor currents as well as flywheel currents over the acceleration event can be seen in Fig. 8. Because of the simple single throttle signal sent to the flywheel during pre-charging, the flywheel current exceeded 50 amps during pre-charging, a more sophisticated pre-charging algorithm would keep this value below 50 amps while placing the same amount of energy in the flywheel. The flywheel motor controller also supplied current to the flywheel between 17 seconds and 24 seconds when no current was necessary, resulting in an overall current draw out of the battery slightly over 50 amps. More tuning of the internal parameters within the motor controller could likely eliminate this current supply, and keep the current draw out of the battery below 50 amps.

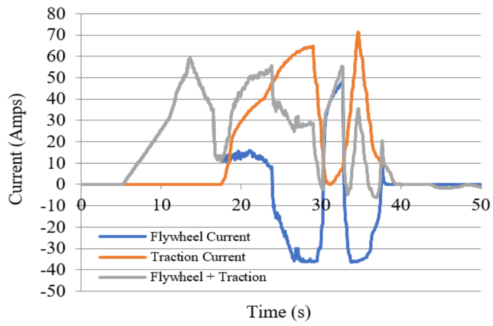


Fig. 8. Currents to traction motors and flywheel during pre-charge experiments

The traction motor current demand during the acceleration events reach approximately 64 amps during the first power peak, and approximately 70 amps during the second charging peak. Using the energy stored in the flywheel from pre-charging, the current out of the battery (Flywheel + Traction line in Fig. 8) was reduced to just slightly over 50 amps. Further improvements to the algorithms could likely reduce the battery current draw even further. The reduction in battery discharge current would have a direct impact on the service life of the battery, increasing its usable lifetime.

D. Experimental Discussion

The goals of the regenerative braking experiments were to keep the battery charging currents below 10 amps, and to achieve an energy usage close to full regeneration potential. The open loop control algorithm was able to largely keep the battery charging currents below the desired 10 amps level. With a more complex algorithm, it is likely that all battery charging currents could be kept below the desired 10 amp level. The energy usage of the system was slightly more than the minimum energy used by a hybrid vehicle with a 10 amp regeneration limit.

The increase over a traditional hybrid vehicle can be attributed to less than optimal control algorithms, and a driving profile greatly reduced in magnitude. If the magnitude of the driving profile were increased, the number of regenerative peaks over 10 amps would also increase, necessitating more energy being sent to the flywheel, and increasing the system effectiveness. On the algorithm side, the open loop control algorithm used to send energy to the flywheel often sent more energy than necessary to the flywheel. It is desired to have the minimum amount of energy sent to the flywheel, because the flywheel has a motor efficiency as well as parasitic losses associated with it. Through optimization of the control algorithms, it is believed that the efficiency of the system can increase and become better than a comparable traditional hybrid vehicle.

The goal of the pre-charging experiments was to investigate if the INSTAR flywheel could be used to offset battery discharge currents during acceleration events. Using slightly modified algorithms already developed for regenerative braking, the flywheel was successfully used to decrease the magnitude of current required from the battery to accelerate the vehicle. The maximum current from the battery during the experiment was slightly over the desired 50 amp level and peaked at 60 amps during the pre-charging event. But further refinement of the pre-charging throttle signals would decrease this current level, and the same amount of energy could be stored in the flywheel with a lower current draw out of the battery. Incorporating pre-charging events into the UDDS may reduce the magnitude of discharge currents coming out of the battery to propel the vehicle, which could increase the service life of the battery. More research into the implementation of pre-charging is necessary in the future.

V. Conclusion

This work shows the potential gains in vehicle efficiency as well as component lifetime which can be had by using a dedicated high-power device, such as an electromechanical flywheel, in a hybrid vehicle. It is clear through increased regenerative braking energy capture, efficiency of the vehicle can be increased. The capture of regenerative braking energy may be placed into the electrochemical batteries, used to accelerate the vehicle, or a combination of the two. It was shown in laboratory experiments that an electromechanical flywheel can be used to capture excess regenerative braking energy, and that this energy can be returned to the electrochemical batteries or traction motors. It was also shown that pre-charging can be used to decrease the current demand out of the vehicle batteries, which may increase the battery service life. More work is needed to improve upon the efficiency of the system and prove that the electromechanical system as tested can yield energy efficiencies better than a traditional hybrid vehicle.

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