Design of a Low-cost Hybrid Powertrain with Large Fuel Savings

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Abstract—This paper presents a new design of a low-cost hybrid powertrain with large fuel savings. The hybrid powertrain contains only low-cost mechanical components, such as a flywheel module and a continuously variable transmission (CVT). No electrical motor/generator or battery is used. Based on characteristics of typical driving cycles, a hybrid topology is introduced and the energy storage capacity of the flywheel module is derived accordingly. The fuel saving potential of the new powertrain is simulated for a compact passenger vehicle, which represents the aimed vehicle segment of the emerging market in China. Simulations show that the fuel saving potential, with respect to the same vehicle without flywheel module, ranges in between 16 and 29%, dependent on the considered driving cycle.

Keywords—“Hybrid powertrain”, “Continuously Variable Transmission (CVT)”, “Flywheel”.

1. Introduction

Hybrid vehicles, i.e., vehicles that use a secondary power source, are a promising solution to the problem of reducing the fuel consumption of passenger vehicles. Today's hybrid electric vehicles offer fuel savings typically ranging from 5 to 30%, depending on the degree of hybridization, the reference vehicle and driving cycle, among others. However, the additional cost of most hybrid transmissions, as compared to their conventional counterparts, is relatively high due to costly electric components such as large battery packs, high-power electronic power converters and additional motor(s) and/or generator(s). Plug-in hybrid vehicles and range-extender electric vehicles may even offer larger equivalent fuel savings, but at a significantly higher cost. For the emerging vehicle market in China, large fuel savings are of great interest due to the increasing oil price and stricter becoming environmental legislation. However, such high additional cost may not be acceptable in this highly cost-sensitive market. As a low-cost alternative, this paper presents a new mecHybrid-powertrain design, using a steel flywheel module and a push-belt CVT for energy storage and power transmission, respectively. The modular design is depicted in Figure 1.

The key contributions to the fuel saving potential are:
- the hybrid module allows for hybrid functionalities, such as brake energy recovery, driving on the flywheel and engine shut-off during standstill, which are considered as very effective measures in reducing the fuel consumption [2,3]; and
- upcoming control technologies, such as Slip Control and Extremum Seeking Control, in combination with a modified hydraulic scheme, may improve the transmission efficiency of the CVT, resulting in a potential fuel saving of 4-5% [4,5].

This paper focuses on the design specifications of the new low-cost hybrid system and the fuel saving potential, as a result of the added hybrid functionalities. The fuel saving potential that results from transmission efficiency improvements of the CVT itself is not discussed here.

Figure 1: Low-cost flywheel module applied to a CVT.

The outline of this paper is given as follows: in Section 2, the design specifications of the hybrid system are derived from characteristics of typical driving cycles. In Section 3, the hybrid topology is introduced and its functionalities are explained. Section 4 describes the hybrid powertrain

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model and a rule-based Energy Management Strategy (EMS) for fuel consumption simulations. The simulation results are discussed in Section 5. Finally, Section 6 summarizes the main results in the form of conclusions and provides an outlook on future work.

2. Design Specifications for the Hybrid Powertrain

The design of the hybrid powertrain requires (1) a topology which supports the most-effective hybrid functionalities, (2) sufficient power transmission capacity to support driving and regenerative braking on the secondary power source (i.e., flywheel), and (3) sufficient energy storage capacity to recuperate a large amount of the available brake energy. The design specifications of the hybrid system are derived from characteristics of typical driving cycles.

2.1 Driving cycles

Five driving cycles are considered: the Japan 10-15 mode (JP1015), Japan Cycle ’08 (JC08), New European Driving Cycle (NEDC), Federal Test Procedure 75 (FTP75) and our own real-life driving cycle (Hurk), see Figure 2. The four standard cycles are widely used in the automotive industry for certified fuel consumption measurements. The unknown Hurk driving cycle is added to represent a more aggressive, real-life type of driving.

![Driving cycles](image)

Figure 2: Driving cycles. Japan 10-15 (JP1015), Japan Cycle ’08 (JC08), New European Driving Cycle (NEDC), Federal Test Procedure 75 (FTP75) and our own real-life driving cycle (Hurk).

2.2 Hybrid Functionalities

The driving cycles contain, in general, many coast-downs, a relatively long standing still time and an average low velocity. These situations are very inefficient for conventional engine-driven vehicles, as energy is dissipated during coast downs, fuel is consumed while standing still and the engine is operated in its inefficient region during low power driving. In these situations, a secondary power source may improve the vehicle efficiency. The most effective measures to reduce fuel consumption, with a hybrid powertrain, e.g. as described in [2,3], are:

1. brake energy recuperation (BER);
2. engine shut-off during standing still;
3. elimination of the inefficient part load operation of the combustion engine, e.g., by driving on or “charging” of the secondary power source; and
4. power assistance of the secondary power source such that engine can be down-sized.

For optimal fuel saving, the hybrid powertrain topology needs to support all these functionalities. The fourth functionality however, may not be feasible with the proposed configuration, since it would result in a decelerating engine during high-power demand.

2.3 Power Transmission Capacity

BER is considered as a very effective measure to increase the vehicle efficiency. The recoverable brake energy is limited by the power and energy capacity of the flywheel system and depends on the driving conditions of the vehicle. The recoverable brake energy \( E_{\text{ber}} \), as a function of the power transmission capacity \( P_{\text{cap}} \), is for a given driving cycle defined as

\[
E_{\text{ber}}(P_{\text{cap}}) = \int_0^T \alpha(P(t))\eta(t)\,dt,
\]

where \( T \) is the driving cycle period, \( \alpha \) is the brake distribution, \( \eta \) is the efficiency and \( P(t) \) is the vehicle propulsion power. A typical brake energy distribution is shown in Figure 3. It can be observed that the BER-potential as a function of power transmission capacity is defined by

\[
BER = 100 \cdot \frac{E_{\text{ber}}(P_{\text{cap}})}{E_{\text{max}}},
\]

where obviously no limits on the energy storage capacity are assumed. The BER-potential is an useful measure to specify the required power transmission capacity of the hybrid module, to recover a large portion of the brake energy in the considered driving cycles. The BER-potential, as a function of the power transmission capacity is shown in Figure 3. It can be observed that the BER-potential of the real-life driving cycle is much lower than the standard cycles. As expected, the more aggressive type of driving requires a higher power transmission capacity to recover the brake energy, due to the higher decelerations. Furthermore, it is seen that the slope of the BER-potential decreases with increasing power transmission capacity. This implies that, for the considered driving cycles, a high power transmission capacity is only required for a few brake actions. To capture the majority of the brake energy (>70 %), a power transmission capacity of at least 15 kW is desired. Finally, it can be observed that for the real life cycle, the BER-potential saturates below 100 %. This can
be explained with the allowed brake torque distribution, for vehicle stability.

Figure 3: Recoverable brake energy as a function of the power transmission capacity of the hybrid system.

2.4 Energy Storage Capacity

Besides power transmission capacity, energy storage capacity of the hybrid system also limits the recoverable brake energy. The recoverable brake energy ($E_{ber}$), as a function of the energy storage capacity ($E_{cap}$) is for a given driving cycle defined as follows. For each BER action, the stored energy is calculated during braking ($P_v(t) \leq 0$) by

$$E_{ber}(E_{cap}) = \int_{t_1}^{t_2} a(P_e)\eta P_v(t) \, dt,$$

$$0 \leq E_{ber}(t) \leq E_{cap}, \quad E_{ber}(t_1) = 0,$$

(3)

with initial braking time $t = t_1$ and final braking time $t = t_2$. After the braking action, the recovered energy will be used to propel the vehicle ($P_v(t) > 0$), according to

$$E_{ber}(E_{cap}) = \int_{t_3}^{t_2} \eta P_v(t) \, dt,$$

$$0 \leq E_{ber}(t) \leq E_{cap}, \quad E_{ber}(t_3) \leq 0.$$

(4)

At time $t = t_3$, all recovered brake energy is used to propel the vehicle, and the BER action finishes. In case another brake action intervenes, equations (3) and (4) are repeated. In the above process, no limits on the power capacity of the flywheel system are assumed, and furthermore energy losses during standstill are assumed to be negligible. An example of such recovery action is shown in Figure 4.

Figure 4: Example of brake energy recovery action during a brake action on the NEDC, using a hybrid system with unlimited and limited energy storage capacity.

As shown, the stored energy level increases during braking and decreases during driving. The arrows indicate the recoverable brake energy. In this example, it is seen that an energy storage capacity of 25 kJ is insufficient to recover all brake energy.

The BER-potential as a function of energy storage capacity is defined by

$$BER_E = 100 \cdot \frac{E_{ber}(E_{cap})}{E_{max}},$$

$$E_{max} = \lim_{E_{cap} \to \infty} (E_{ber}(E_{cap})).$$

(5)

The BER-potential, as a function of the energy storage capacity is shown in Figure 5.

Figure 5: Recoverable brake energy as a function of the energy storage capacity of the hybrid system.

It is seen that both the standard driving cycles as well as the real-life cycle show similar results. Only the NEDC cycle shows different behavior, which can be explained by the brake event at the end of the cycle (120 km/h to standstill), see Figure 2. To capture the majority of the brake energy (>70 %), an energy storage capacity of at least 50 kJ is desired. Note that this is a net energy, since for most energy buffers, such as flywheels or batteries, certain state-of-charge limits have to be considered that reduce the effective energy content.

3. Hybrid Powertrain Design

Based on the driving cycle analysis, a new hybrid powertrain design is presented, using a steel flywheel module and a push-belt CVT. This section describes the powertrain topology and sizing of the flywheel module.

3.1. Hybrid Powertrain Topology

The hybrid powertrain topology is depicted in Figure 6. This topology supports all the hybrid functionalities as described in Section 2, except for power assist. Four quasi-static operation modes may be identified, in which none of the clutches is slipping:

- **Standstill** (mode 0): engine is shut off, flywheel may be spinning;
- **Flywheel Driving** (mode F): engine is shut off, the push-belt CVT is used to propel the vehicle with the flywheel, or to recuperate brake energy;
• Flywheel Charging (mode F+E): the engine is used to “charge” the flywheel and propel the vehicle simultaneously, while the push-belt CVT is used to control the power split ratio between the flywheel and the vehicle;
• Engine Driving (mode E): the engine is used to propel the vehicle, e.g., in case the maximum speed ratio of the CVT is reached.

These operation modes are schematically depicted in Figure 7.

Figure 6: Hybrid powertrain topology with flywheel (FW), internal combustion engine (ICE), vehicle load (VL), Continuously Variable Transmission (CVT), clutches ($C_f$, $C_r$, $C_t$) and brake.

Figure 7: Four quasi-static operation modes in which none of the clutches is slipping: Standstill (0), Flywheel Driving (F), Flywheel Charging (F+E) and Engine Driving (E).

This topology supports the hybrid functionalities, as described in Section 2, as follows:

1. brake energy is recuperated in mode F or F+E;
2. the engine is shut off in mode 0 and restarted when shifting from mode 0 to F to F+E, with slipping clutches $C_f$ and $C_r$ during the shifts;
3. inefficient part load operation of the engine is eliminated by flywheel driving in mode F (no load) or flywheel charging in mode F+E (high load).

The effectiveness of these hybrid functionalities strongly depends on the sizing of the flywheel module and the Energy Management Strategy (EMS), which controls the hybrid powertrain. The latter will be discussed in Section 4.

3.2. Sizing of the Flywheel Module

An important parameter in the hybrid powertrain is the sizing of the flywheel. A large power transmission capacity and energy storage capacity may improve the fuel saving potential, as shown in Section 2, but at the cost of rising production costs, packaging complexity and safety risks. For a flywheel module, the power transmission capacity is mainly limited by the maximum transmissible torque of the CVT, during regenerative braking. This is assumed to be 100 Nm at the primary shaft of the CVT. Further information regarding regenerative braking through a CVT can be found in [9]. The energy storage capacity is mainly limited by the flywheel mass (production costs, packaging) and maximum operation speed (safety). Taking these aspects into account, a flywheel module is chosen with a power transmission capacity of 25 kW and an energy storage capacity of 150 kJ. A detailed balance between the design criteria falls beyond the scope of this paper. The combination of a relatively high power transmission capacity with a relatively low energy storage capacity is very suitable for the use of flywheels, in terms of efficiency and hardware design [10,11]. Characteristics of the flywheel module can be found in Table 1.

4. Simulation Model

The fuel-saving potential of the hybrid powertrain is simulated with a detailed drive train model and controlled with a heuristic EMS. The characteristics of the drive train base components are summarized in Table 1. The efficiency models of the engine, flywheel and transmission are based on warm operation conditions. The reference vehicle, i.e., Fiat-500, represents the aimed vehicle segment of the emerging market in China. The powertrain is represented by a forward-facing (or integrating) model, which implies that the input is the driver’s pedal and the output is the resulting vehicle velocity. The pedal position is interpreted as a desired torque and controlled by a driver model that tries to track the driving cycle. The EMS tries to track the desired torque, by controlling the powertrain components, i.e., the engine torque, clutch pressures, CVT shift speed and the brake torque. For now, a heuristic rule-based EMS is used, to show the feasibility of the concept.
Table 1: Base Component Characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>4-cylinder 1.3l VVTi internal combustion engine, peak power 64 kW (at 6000 rpm), peak torque 124 Nm (at 4400 rpm), peak efficiency 244 g/kWh</td>
</tr>
<tr>
<td>Flywheel</td>
<td>Vacuum-placed (100 mbar) 150-kJ steel flywheel, inertia 0.03 kgm², max. speed 30,000 rpm, gear ratio 1:12, peak friction 300 W (at 30,000 rpm)</td>
</tr>
<tr>
<td>Transmission</td>
<td>Push-belt driven Continuously Variable Transmission, max. input torque 140 Nm, ratio range 6.0, final drive ratio 1:5.41, integrated dual-stage pump, peak efficiency 91%</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Fiat-500 (2007), mass 930+150 kg, aerodynamic drag coefficient 0.30, frontal area 1.7 m²</td>
</tr>
</tbody>
</table>

1. Engine data is based on measurements.
2. Flywheel data is based on theoretic and validated models.
3. Transmission data is based on a validated model.
4. Vehicle data is based on theoretic model.

Figure 8 shows the principle behind the used EMS: during standstill the engine is shut-off (0); during low power demand the flywheel is used (F); during low-speed accelerations the flywheel is charged (F+E); during continuous medium and high power demand the engine is used (E) and during braking the flywheel is charged (F). The rules are set by engineering experience, which may result in a fuel consumption that is sub-optimal.

Figure 8: Example of the hybrid operation modes on a driving cycle, with Standstill (0), Flywheel Driving (F), Flywheel Charging (F+E) and Engine Driving (E).

5. Simulation Results

Two types of simulations are performed for all considered driving cycles: (1) fuel-optimal engine operation (E-line tracking) without using the flywheel module; and (2) hybrid driving using the flywheel module with the EMS as described in Section 4. For all simulations, a warm powertrain is assumed, in spite of the fact the NEDC and FTP-75 officially starts with a cold engine. The initial (scaled, i.e., reduced to the primary shaft) flywheel speed equals 200 rad/s and it is observed that with each driving cycle, the flywheel speed approximately returns to the initial speed. Hence, no energy is added or removed. Figure 9 shows the simulation results of hybrid driving on the NEDC. The upper graph shows the operation modes together with the vehicle velocity. It can be seen that the operation modes, more or less, resembles the EMS principle as described in Section 4. The bottom graph shows the corresponding speeds of the primary shaft of the CVT, engine and flywheel. It can be seen that especially during the urban parts, the flywheel is used intensively.

Figure 9: Simulation results. Operation modes of the hybrid powertrain for the NEDC (upper) and corresponding speeds of the primary shaft of the CVT, engine and flywheel (bottom).

The results of the considered driving cycles are shown in Figure 10. The fuel-saving potential ranges between 16 and 29 %, dependent on the considered driving cycle. The highest fuel saving potentials correspond to driving cycles (JP 10-15, JC ’08, Hurk) with a relatively long standing still time and relatively low vehicle velocities, see Figure 1. This can be explained with the hybrid functionalities of the flywheel module, as described in Section 2.2.

Figure 10: Simulation results. Fuel saving potential with the flywheel module.

6. Conclusions

This paper has presented a new low-cost hybrid powertrain design that uses a steel flywheel and a push-belt CVT for energy storage and transmission respectively. A hybrid topology is proposed, that supports the most-effective hybrid functionalities: (1) brake energy recuperation for later use; (2) engine shut-off during standstill; and (3) elimination of the
inefficient part load operation of the combustion engine. The power- and energy storage capacity of the flywheel module are sized, based on the analysis of five typical driving cycles. With a power- and energy storage capacity of 25 kW and 150 kJ respectively, almost 80% of the brake energy can be recovered. Simulations show that the fuel saving potential of the flywheel module, with respect to the same vehicle without flywheel module ranges between 16 and 29%, dependent on the considered driving cycle. Even though the results are very promising, further research in the EMS is required to improve the fuel consumption even more. Therefore, future work will focus on the design of an optimal EMS, which minimizes the fuel consumption without compromising comfort aspects such as noise and vibrations. The developed controls will be applied to the, currently under development, meCHybrid-demonstrator vehicle, planned by late 2012.

7. References


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