Mechanical CVU for automotive KERS

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Abstract: The kinetic energy recovery in braking via electrical or mechanical hybrid systems is being considered as one promising short-range solution to improve the fuel economy of ground vehicles.
The key element of a mechanical hybrid is a variable drive (CVU), which is used to manage the transmission of power between the flywheel and the vehicle. The energy performance of the KERS depends on the efficiency and the ratio spread of the CVU: optimal features are a large ratio spread and a very good efficiency in both direct and reverse operation. Extended range shunted CVT systems made of one CVT, one fixed ratio drive and one planetary gear drive, permit to arrange a CVU with a larger ratio spread than the CVT or to improve CVU efficiency. For this reason they are sometimes suggested in the literature for application to KERS.
In this paper the mechanical efficiency of Power-Split CVTs is investigated, and analytical formulas are determined to calculate the efficiency of the transmission in both direct and reverse operation. Moreover, the effect of the ratio spread of PS-CVT on the energy recovery and overall round-trip efficiency of KERS is investigated by an inverse dynamics simulator of the vehicle driveline with KERS. All internal power circulation modes are simulated in order to suggest which of them is the most effective for application to KERS. The performances of the KERS driven by PS-CVTs are also compared with those achieved with direct drive CVT.

Key–Words: CVT, Power Split transmission, KERS

1 Introduction

Improving fuel economy and reducing the pollutant emissions of ground vehicles is presently one of the most interesting challenges of the vehicle industry. Research is focusing on short, medium and long range solutions. Electric Vehicles (EVs) are the most favoured candidates for the long range, whereas in the short-medium, hybrid vehicles are a more feasible solution. In the short-medium range, the key winning features of hybrid vehicles are basically three: 1. driving range is comparable to traditional internal combustion engine vehicles 2. the power flow can be managed from two (or more) energy sources to optimize the efficiency reducing the pollutant emissions for any given torque-speed demand of the driver; 3. energy recovery in braking. Kinetic Energy Recovery Systems (KERS) can be based upon different principles [1, 2, 3] (basically hydraulic, mechanical, electrical, ...) but share the same purpose: the kinetic energy of the vehicle should not be dissipated in brakes. The KERS must take the kinetic energy from the vehicle during braking, store it in a storage device and then reuse it to accelerate the vehicle. Presently the electrical system is the commonest, being the only one that is used in Formula 1. Electrical system involves several energy transformations, and overall round-trip efficiency is about 30-35%. For this reason, in mainstream automotive applications one promising solution is the mechanical hybrid system, which involves no energy transformation. In the mechanical KERS the high-speed rotating flywheel is the storage device and a stepless transmission is used to manage the power flow from-to the flywheel. Originally developed for Formula 1 motorsport [1], the CVT/flywheel system provides a highly efficient hybrid with half the weight and size than the conventional battery-based system. In the flywheel KERS the energy transfer does not imply any energy conversion: the kinetic energy is simply removed from one source and reallocated to the other. This working principle gives the best round-trip efficiency when compared to other systems in which energy conversions are involved. For instance, it is claimed [1, 4] that the round-trip efficiency of a mechanical KERS is of order 70%, about twice the efficiency of electrical KERS.
Computational results shown in [4] demonstrate that a fuel economy improvement up to 25% can be obtained

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in mainstream passenger cars and a similar result can also be obtained in trucks. Moreover, the KERS is an additional source of power that gives the possibility of engine downsizing with good results in terms of reduction of fuel consumption and CO_2 emissions.
The mechanical variable drive (CVU), which is often used to improve the fuel economy ([5]), plays a key role for an effective operation of mechanical hybrid systems. As shown in [6, 7] the full toroidal traction drive [8] is a suitable choice for application to KERS. Tests were performed with the XTrac P662 full toroidal traction drive with a ratio spread of about 6. Efficiency up to circa 90% were measured with a power capacity of 110kW claiming that it is feasible for application to KERS for both F1 and mainstream vehicles.
Because of the limited extent of ratio range the energy recovery undegoes a limitation. One possible solution to improve the performances is to increase the ratio range of the CVU via an increased range shunted CVT [9, 10]. It is known that in a single mode shunted CVT arrangement (hereafter Power Split CVT or PS-CVT) there are three possible internal power circulation types [11] which affect the efficiency: the reverse internal circulation (Type I), the forward internal circulation (Type II) and the power split (Type III, no re-circulation). The internal power re-circulation has the undesired side-effect to affect the overall efficiency as shown in Refs. [11, 12, 13, 14, 15, 16, 17]. Finally, in the mechanical hybrid the CVU must drive the power two-way (flywheel-to-vehicle and vehicle-to-flywheel) and so it should have a good efficiency in both direct and reverse operation (reversibility). The performance of PS-CVT in both direct and reverse drive has also been investigated in [18] where it is shown that the internal power circulation affects the reversibility of the PS-CVT variable drive.
In this paper the mechanical efficiency of Power-Split CVTs is investigated, and analytical formulas are determined to calculate the efficiency of the transmission in both direct and reverse operation. Moreover, the effect of the ratio spread of PS-CVT on the energy recovery and overall round-trip efficiency of KERS is investigated by an inverse dynamics simulator of the vehicle driveline with KERS. All internal power circulation modes, of which the principles are briefly reviewed, are simulated in order to suggest which of them is the most effective for application to KERS. The performances of the KERS driven by PS-CVTs are also compared with those achievable by direct drive CVT. Simulations of urban FTP-75 driving schedule have been performed varying the ratio spread over a wide range, from Infinitely Variable Transmission (IVT) to reduced range-increased efficiency PS-CVT to understand if a proper ratio spread can be found to optimize the performances of a PS-CVT based mechanical hybrid.

2 The PS-CVT transmission

The main kinematic relations are here derived for a PS-CVT with OS arrangement. The following transmission ratios are defined:

$$\begin{aligned} \tau_{PS} &= \tfrac{\omega_6}{\omega_1} \\ \tau_{CVT} &= \tfrac{\omega_5}{\omega_4} \\ \tau_{FR} &= \tfrac{\omega_4}{\omega_2} \end{aligned} \tag{1}$$

Moreover, the following equation can be written (PG kinematics):

$$\omega_3 + \chi\omega_5 - (1+\chi)\omega_6 = 0 \tag{2}$$

From Eqs. (1-2) and considering that $\omega_1 = \omega_2 = \omega_3$ it follows immediately that:

$$\tau_{PS} = \frac{1 + \chi\tau_{FR}\tau_{CVT}}{1+\chi}. \tag{3}$$

The transmission ratios of the CVT and of the PS are lower and upper bounded within the limits $\tau_{CVT_{min}}$ and $\tau_{CVT_{max}}$ and $\tau_{PS_{min}}$ and $\tau_{PS_{max}}$. The ratio spreads are defined:

$$\begin{aligned} rr_{CVT} &= \tfrac{\tau_{CVT_{max}}}{\tau_{CVT_{min}}} \\ rr_{PS} &= \tfrac{\tau_{PS_{max}}}{\tau_{PS_{min}}} \end{aligned} \tag{4}$$

It has been widely shown [11] that in the case of a pure mechanical CVT with a finite and positive ratio spread rr_{CVT} and with $rr_{CVT} < rr_{PS}$, two internal power flows are possible: the Type I power flow, also called reverse circulation mode, and the Type II power flow, also called the forward circulation mode. Power flow of Type III (Power Split Mode) can be achieved only if $rr_{CVT} > rr_{PS}$.
The lower and upper bounds of the τ_{CVT} are fixed, being an intrinsic feature of the device. Some lower and upper bounds of τ_{PS} have to be fixed. With the condition $rr_{CVT} < rr_{PS}$ there are two possible choices to design the transmission: the first one is to have a monotonic increase of the τ_{PS} when the τ_{CVT} increases; the second one is to have a monotonic decrease. Two simple systems of two equations with the two unknown quantities τ_{FR} and χ can be solved by imposing those two conditions [18]. In the former case a power flow of Type II is obtained, whereas in the latter case there is a reverse power circulation of Type I.
A discussion follows with the following further hypotheses: the efficiency of the PG, named η_{PG} will be considered equal to 1 and the efficiency of the CVT and of the FR will be considered constant.

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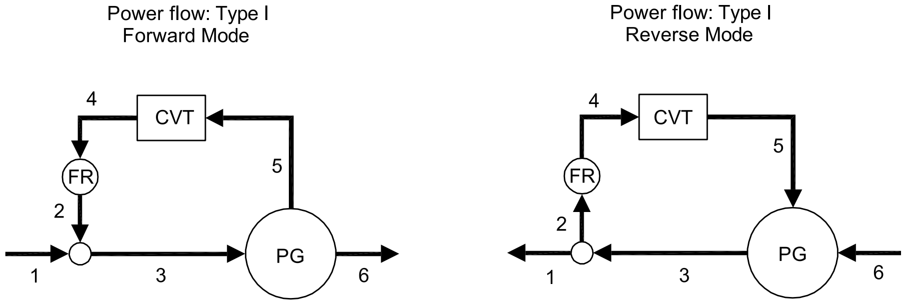

(a) (b)

Figure 1: Schematic picture of the internal power circulation of Type I in an Output Split PS-CVT with a forward (a) and reverse (b) power transmission.

2.1 Type I power flow

If τ_{PS} is a decreasing function of the τ_{CVT}, then a power flow of Type I is obtained. The internal power flow type is not affected at all by the main power flow direction, because under the hypotheses $rr_{PS} > 0$ and $rr_{CVT} > 0$ the angular velocities do not change their direction, and so all the torques have to change when switching from forward to reverse operation. Power flow of type I is depicted in Figures 1 for both forward and reverse power transmission.

Forward power transmission

A qualitative analysis of the efficiency in this case leads to the conclusion that the transmission of power is always allowed. It is important to notice that, given a value of τ_{PS}, the ratios of the torques and the angular velocities of PG shafts are fixed, and so the ratios between the powers $P_3,\ P_5,\ P_6$ are fixed too. Considering the Figure 1a, $|P_6| = |P_3| - |P_5|$ that means that $|P_3| > |P_5|$. Because of the direction of power flow through the CVT branch, $|P_2| < |P_5|$ because $|P_2| = \eta_{CVT}\eta_{FR}\,|P_5|$. In the end, $|P_1|$ must be larger than $|P_6|$ but it is always possible to transfer the power from 1 to 6. The analytical expression of the efficiency of the PS-CVT with type I power with forward power transmission is:

$$\eta_{PS}^{I,forward} = \frac{\tau_{PS}(1+\chi)}{(1-\eta_{CVT}\eta_{FR}) + \eta_{CVT}\eta_{FR}(1+\chi)\tau_{PS}} \tag{5}$$

where $\eta_{PS}^{I,forward} = P_6/P_1$, $\eta_{CVT} = P_4/P_5$, and $\eta_{FR} = P_2/P_4$. It follows immediately from Eq. (5) that $\eta_{PS}^{I,forward} = 0$ only if $\tau_{PS} = 0$ that is the case of the IVT transmission (see [12, 13]), not the one analysed in this paper.

Reverse power transmission

In this case, it can be demonstrated that a low efficiency of the CVT branch can lead to the impossibility to transfer power from 6 to 1. The internal power flow is such that $|P_6| = |P_3| - |P_5|$ (see Fig. 1b) which means that $|P_3| > |P_5|$. However, $|P_2| > |P_5|$ because $|P_2| = |P_5|/(\eta_{FR}\eta_{CVT})$. Because $|P_1| = |P_3| - |P_2|$, if the condition $|P_3| - |P_2| < 0$ occurs, it means that the transmission of power from 6 to 1 is impossible. This condition is easier obtain when the ratio $|P_5|/|P_3|$ is large, or when the efficiency of the CVT branch is very low. The analytical expression of the efficiency of the PS-CVT with type I power flow and in the reverse power mode is:

$$\eta_{PS}^{I,reverse} = \frac{\tau_{PS}(1+\chi) - (1-\eta_{CVT}\eta_{FR})}{(1+\chi)\eta_{CVT}\eta_{FR}\tau_{PS})} \tag{6}$$

where $\eta_{PS}^{I,reverse} = P_1/P_6$, $\eta_{CVT} = P_5/P_4$, and $\eta_{FR} = P_4/P_2$. A value of τ_{PS} exists below which $\eta_{PS}^{I,reverse} < 0$. The power flow can not be of reverse type if:

$$\tau_{PS} < \frac{1-\eta_{CVT}\eta_{FR}}{(1+\chi)} = \tau_{PS}^{I,*} \tag{7}$$

Such a limiting value corresponds to an actual working condition only if it belongs to the range $[\tau_{PS_{min}},\ \tau_{PS_{max}}]$. This condition occurs only if:

$$rr_{PS} > \frac{rr_{CVT} - \eta_{CVT}\eta_{FR}}{rr_{CVT}(1-\eta_{CVT}\eta_{FR})} = rr_{PS}^{I,*} \tag{8}$$

2.2 Type II power flow

If τ_{PS} is an increasing function of the τ_{CVT} then the power circulation is of Type II. Power flow of type II is depicted in Figure 2, for both forward and reverse power transmission.

Forward power transmission

Similar calculations as those described in the previous section lead to:

$$\eta_{PS}^{II,forward} = \frac{\eta_{CVT}\eta_{FR}(1+\chi)\tau_{PS}}{\tau_{PS}(1+\chi) - (1-\eta_{CVT}\eta_{FR})} \tag{9}$$

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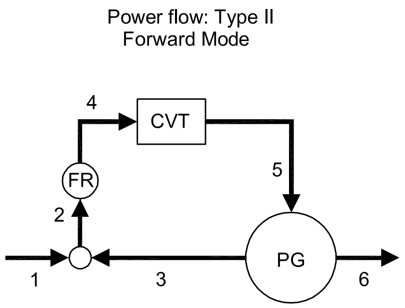


(a) (b)

Figure 2: Schematic picture of the internal power circulation of Type II in an Output Split PS-CVT with a forward (a) and reverse (b) power transmission.

where $\eta_{PS}^{II,forward} = P_6/P_1$, $\eta_{CVT} = P_5/P_4$, and $\eta_{FR} = P_4/P_2$. It follows immediately from Eq. (9) that $\eta_{PS}^{I,forward} = 0$ only if $\tau_{PS} = 0$ (IVT).

Reverse power transmission

The analytical expression of the efficiency of the PS-CVT with type I power flow and in the reverse power transmission is:

$$\eta_{PS}^{II,reverse} = \frac{\eta_{CVT}\eta_{FR}(1+\chi)\tau_{PS} + (1-\eta_{CVT}\eta_{FR})}{(1+\chi)\tau_{PS}} \quad (10)$$

where $\eta_{PS}^{I,reverse} = P_1/P_6$, $\eta_{CVT} = P_4/P_5$, and $\eta_{FR} = P_2/P_4$. A value of τ_{PS} exists below which $\eta_{PS}^{II,reverse} < 0$. The power flow can not be of reverse type if:

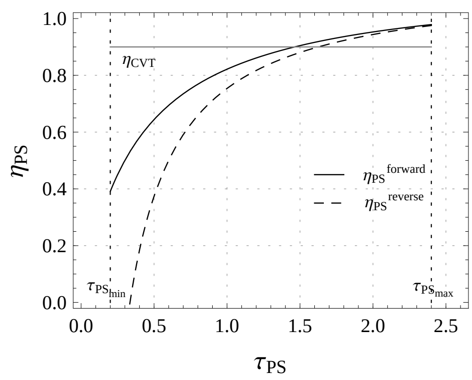
$$\tau_{PS} < \frac{\eta_{CVT}\eta_{FR} - 1}{\eta_{CVT}\eta_{FR}(1+\chi)} = \tau_{PS}^{II,*} \quad (11)$$

$\tau_{PS}^{II,*}$ corresponds to an actual working condition only if it belongs to the range $[\tau_{PS_{min}}, \tau_{PS_{max}}]$. This condition is satisfied if:

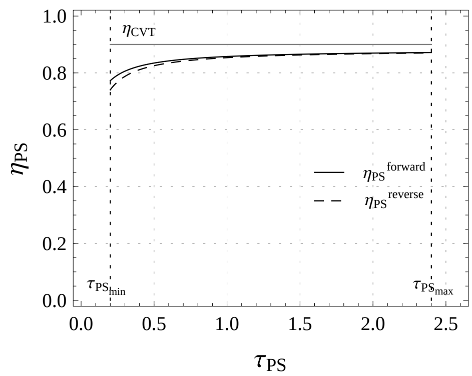
$$rr_{PS} > \frac{rr_{CVT} - \eta_{CVT}\eta_{FR}}{1-\eta_{CVT}\eta_{FR}} = rr_{PS}^{II,*} \quad (12)$$

2.3 Numerical example

Figure 3 shows the results of the Equations (5,6) for Type I power flow. The efficiency η_{PS} is a function of the τ_{PS}. In the forward transmission mode it is always larger than in reverse mode (black dashed line) and it is always positive i.e. that the power can always be transmitted from shaft 1 to 6. At large values of the ratio τ_{PS} the efficiency is large, (larger than the η_{CVT}). Otherwise, with low values of τ_{PS} the efficiency degrades very rapidly. In the reverse mode it is always less then in the forward. The two efficiencies approach with large τ_{PS} whereas, with small τ_{PS}, the efficiency in the reverse flow can also be negative at $\tau_{PS}^{I,*}$ i.e. the transmission of power from shaft 6 to 1 is not allowed ($\tau_{PS} < \tau_{PS}^{I,*}$).



(a)



(b)

Figure 3: The efficiency of the PS-CVT with a power flow of type I (a) and II (b). The grey line is the η_{CVT}, which is supposed to be constant, the black continuous line is the η_{PS} in forward main power flow, the dashed line is the η_{PS} in reverse main power flow. Lower and upper bounds of τ_{PS} are also emphasized.

The results of the Eqs. (9,10), referring to a Type

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II power flow, are shown in the Figure 3. In the forward transmission mode the efficiency (continuous black line) is always larger than in reverse mode (black dashed line). However the difference between them is very small and tends to become meaningful only at small values of τ_{PS}. With the data of this numerical example, the transmission of power is always allowed in both forward and reverse modes because $\tau_{PS}^{II,*} < \tau_{PS_{min}}$. A disadvantage of Type II power flow is that the efficiency is always smaller than η_{CVT} (continuous gray line).

3 Effect of the ratio spread on the performance of KERS

The effect of the ratio range of the PS-CVT is then calculated. Simulations of a compact car following a FTP-75 driving schedule have been performed with an inverse dynamics simulator ([21]). The ratio spread is changed varying $\tau_{PS_{min}}$ in the range $[0, 1]$ and keeping the maximum value $\tau_{PS_{max}} = 2.5$ constant. With those values, the ratio spread of the CVU (PS-CVT) varies within the range $[2.5, +\infty]$. The performance of KERS have been studied via two parameters namely the KERS boost and the KERS round-trip efficiency (Ref. [21]). The KERS boost is the energy that the KERS provides to the vehicle, divided by the overall energy demand of the driving schedule (per cent). The round trip efficiency is the energy which is actually reused divided by the energy which could be recovered with KERS in one cycle.

Figure 4a shows the KERS boost as a function of the $\tau_{PS_{min}}$. In the first range $0 < \tau_{PS_{min}} < \tau_{CVT_{min}} = 0.4$ the PS-CVT is an increased range shunted CVT. Two internal power circulation modes are possible: Type I and Type II. Both have been investigated. KERS boost is larger with a power flow of Type II than with Type I, with a gap of about 4% for all values of $\tau_{PS_{min}}$. With $\tau_{PS_{min}} < \tau_{CVT_{min}} = 0.4$ the KERS boost is not much sensitive on the $\tau_{PS_{min}}$ and ranges between 20% and 21%. It has a local maximum (optimum) close to $\tau_{PS_{min}} = 0.25$ corresponding to $rr_{PS} \simeq 10$. With $\tau_{PS_{min}} = \tau_{CVT_{min}} = 0.4$ the PS-CVT is replaced with a direct drive CVT. The KERS boost is about equal to 22%. In the second range where $\tau_{CVT_{min}} < \tau_{PS} < 1$, the power flow is of Type III ([11, 20]) and the PS ratio range is smaller than the CVT's ($rr_{PS} < rr_{CVT}$). The KERS boost (Fig. 4a) strictly decreases as the $\tau_{PS_{min}}$ is increased (or, equivalently, rr_{PS} is decreased). Qualitatively similar results are those of KERS round-trip efficiency, shown in Figure 4b. The maximum value of the round-trip efficiency is the one of direct drive CVT, which results equal about to 70%.

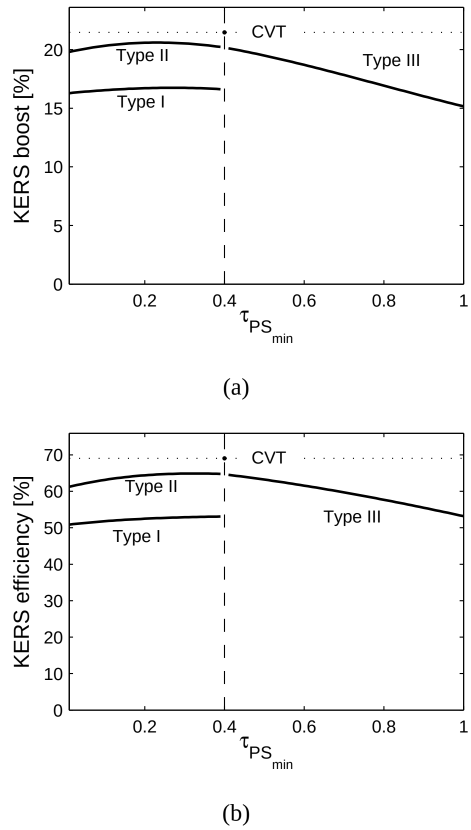

Figure 4: (a) The KERS boost and (b) the round-trip efficiency in the FTP-75 driving schedule as a function of the lower bound of the PS-CVT ratio $\tau_{PS_{min}}$. The results are shown considering the internal power flows of Type I, Type II and Type III and the direct drive CVT (full toroidal traction drive [19]). The horizontal dotted line emphasize the value given by the system with direct drive CVT (marked with a dot).

4 Conclusions

In this paper, simple formulas have been determined to understand the relationship between the PS architecture and the efficiency for both forward and reverse operation. It has been demonstrated that the PS-CVT with a ratio spread larger than a CVT's, is not always reversible depending on the actual efficiency of the CVT and FR and on the internal power flow of PS. Moreover, the effect of the ratio range of mechanical CVU with shunted CVT architecture (PS-CVT) on the performance of mechanical KERS has been investigated. The round-trip efficiency and the KERS boost have been calculated as performance indexes through the simulation of a compact car in urban

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FTP75 driving schedule. It has been shown that the inverse circulation of power (Type II) inside the PS-CVT gives the best performances because in this case the efficiency of the variable drive is good (even if always less then the CVT's) in both direct (vehicle acceleration) or reverse mode (flywheel acceleration). It is found that there is an optimum value of ratio spread in terms of KERS boost or round-trip efficiency but the performance of a direct drive CVT are slightly better than PS-CVT's because of larger efficiency.

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