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KERS DYNAMICS
(KINETIC ENERGY RECOVERY SYSTEMS)

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Abstract: *The following paper reflects upon the dynamics of mechanical systems which can store the kinetic energy of vehicles during the braking sequence. The efficiency of these systems is much higher in comparison with the electrical systems which convert mechanical energy to electricity which after is stored in electrochemical batteries. These systems based on batteries have both increased prices and low energy conversion efficiency. At the beginning of the paper there are presented some technical solutions used by diverse manufacturers for energy storage in flywheels which can rotate with an increased efficiency at high rotations speeds (60,000 rpm). For these systems, the energy is being stored during the braking sequences of the vehicle. Further in the paper by using a scheme imagined by the authors, the dynamic analysis of the mechanical system with high speed flywheel is realised. This flywheel system allows in the same time the storage of kinetic energy during braking and its release to the vehicle's wheels when needed. In the numerical application which was developed, the stored mechanical energy is determined and also the maximum peak power given by the mechanical system. The end of the paper denotes the conclusions regarding the possibility of using such systems in the composition of the mechanics of hybrid vehicles.*

Keywords: KERS, mechanical system, flywheel, CVT, IVT, rotation speed dimmers, planetary transmission.

INTRODUCTION

In a world in which the conservation of natural resources became a priority, the problem of vehicles energy losses became more and more important. In the automotive sector, a high energy loss appears on deceleration or braking. This problem was solved by introducing the regenerative braking systems.
Regenerative braking is realised with systems that reduce the vehicle's speed by converting the translation kinetically energy into another form of energy. In the case of a hybrid vehicle powered by an electrical motor supplied with energy from batteries when the vehicle brakes the motor is rotating in the reverse direction working like an electricity generator. The instant effect is that the vehicle decelerates. The electricity produced this way is directed toward the batteries which stores it as chemical energy. When it's needed, the batteries supplies the stored energy back to the wheels adding in this way a power surplus. Unfortunately, the majority of energy conversion processes (from mechanical energy to electricity and from electricity to chemical energy) reduce the global efficiency of the system below 30%. This deficit is overthrown by the mechanical hybrid.
The mechanical system based on flywheels is made from a rotating flywheel, a continuously variation transmission (*CVT*) and a mechanical system connected through a clutch. A system like this is named *KERS* (Kinetic Energy Recovery System). When the vehicle brakes or decelerates the flywheels stores rotational kinetic energy, allowing itself to rotate with about 60.000 rpm. When the vehicle stops or when the flywheel reaches its peak rotation speed, the flywheel is disconnected from the transmission

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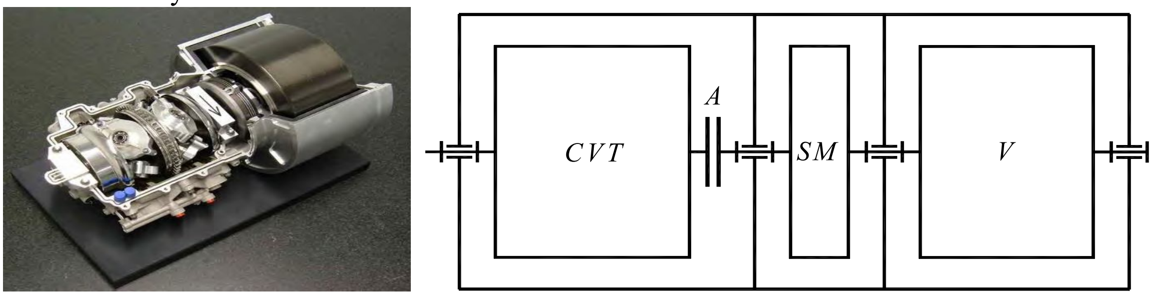
by a clutch. If the vehicle lacks energy, the clutch reforges the connection and the flywheel transfers the energy back to the wheels through a *CVT*.

DIFFERENT TYPES OF KERS USED

The *KERS* system was firstly professional designed and made for F1 cars. The first high quality system that used a flywheel was made by the company *Flybird Systems* [5].
During the passing of years there were developed different types of systems of this kind by a large variety of companies. From these we can remind the experimental system made by Volvo [1], presented in fig.1. This system is composed from a toroidal continuously variation transmission with rollers (*CVT*), a link in and out clutch A, a mechanical system SM for rotation speed increase and decrease and a flywheel V.



a) General view *b) Schematic drawing*

Figure 1. The KERS assembly made by Volvo [1].

The flywheel is the element of the system which stores kinetic energy. Because of its high rotation speeds it is positioned in a vacuum enclosure thus allowing a great reduction of air friction losses. The flywheels used can store kinetic energies up to 400 kJ. Because of this, the rotation speed can reach up to 60,000 rpm and the bearings system is very proficient designed. One possible solution for the bearing system is by using magnetic bearing. The company *Waukesha bearings* is a manufacturer of this kind of bearings.
The mechanical system has the role to amplify the movement and to transfer it to the flywheel. Epicyclic gears are used due to their high efficiency and due to their ability to work at very high rotation speeds. The clutch is used to disconnect the flywheel when there is no power exchange but also when the system is idling in order to reduce friction losses.
An optimal power transfer is made with the aid of a continuously variation gearbox which varies the gear ratio function of demand. Volvo used a toroidal gearbox with a single row of rollers whose position determines the gear ratio. In Figure 2 we can see a model of this dimmer with a single row of rollers.

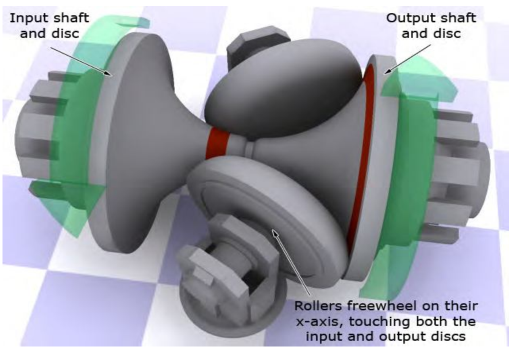


Figure 2. Rotation speed dimmer with discs and a single row of rollers [8].

A second type of *KERS* includes a toroidal continuously variation transmission with two rows of rollers. The schematic of a system of this kind is given by fig.3. In this figure, the inertial flywheel 1 has a mass of 8kg and is made of carbon fibre and can rotate itself with a maximum rotation speed of 60,000 rpm. The flywheel is positioned in a vacuum enclosure 2 which has a sealing element 3. A magnetic clutch 4 can connect or disconnect the flywheel from the rest of the mechanical system. In the vacuum enclosure we find the epicyclical gears 5, the toroidal dimmer with two rows of rollers 6, the gears 7 named *IVT* (Infinite Variation Transmission) and the mechanical system 8 used for torque control. The movement is transmitted through the system 9 which is made of: main transmission, differential and drive shafts which are used to form the link with vehicle's wheels.

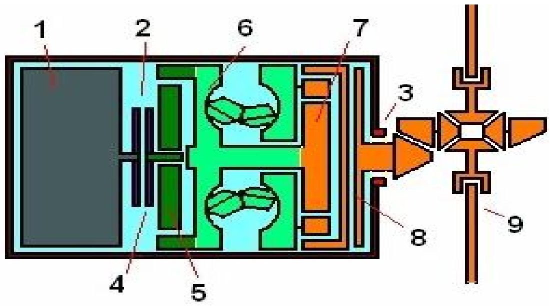


Figure 3. Schematic drawing of a KERS which has a toroidal dimmer with two rows of rollers [8].

A similar system is the one from Figure 4.
The following notations were used: 1 – inertial flywheel made of carbon fibre which can reach a peak rotation speed of 60,000 rpm, 2 – vacuum enclosure, 3 – sealing for high rotation speeds, 4 – epicyclical gears with the gear ratio i_1, 5 – connection clutch for high rotation speeds, 6 – toroidal dimmer with a single row of rollers (*CVT*) which has a maximum gear ratio i_2, 7 – hydraulic system for commanding the *CVT*, 8 – epicyclical secondary gears which forms the gear ratio i_3, 9 – connection clutch used for take-off and 10 – secondary gears with the gear ratios i_4 and i_5. The total gear ratio for a system of this kind is: $i_t = i_1 \cdot i_2 \cdot i_3 \cdot i_4 \cdot i_5$.

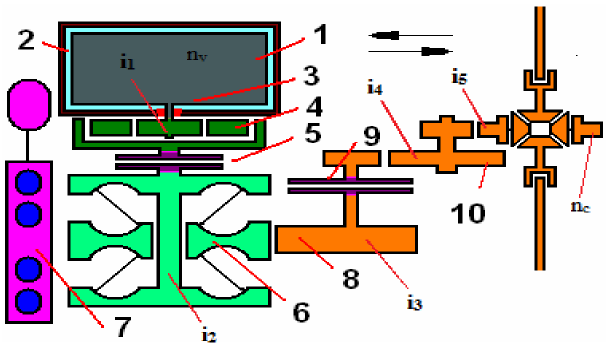


Figure 4. Schematic drawing of a KERS which has a toroidal dimmer with a single row of rollers [8].

The flywheel is without doubt the most important component of a *KERS*. It is able to store kinetic energy when vehicles are braking leading to its increase in angular rotation speed. The quantity of energy which can be safely stored in a flywheel depends upon the point from which the flywheel is in danger of wearing or damaging itself. The flywheels used for *KERS* are generally made from certain materials function of the maximum rotation speed and of system's design. High speed flywheels, for over 30,000 rpm are made of high strength carbon fibre. This solution is used to reduce the mass of the system. Low speed flywheels of below 20,000 rpm are mainly made from steel and other materials which can have a price relatively low.
The weight of the flywheel is a decisive factor used in establishing the systems efficiency.
In Figre 5 we can see the construction model of an inertial flywheel made by Flybird Systems for F1.

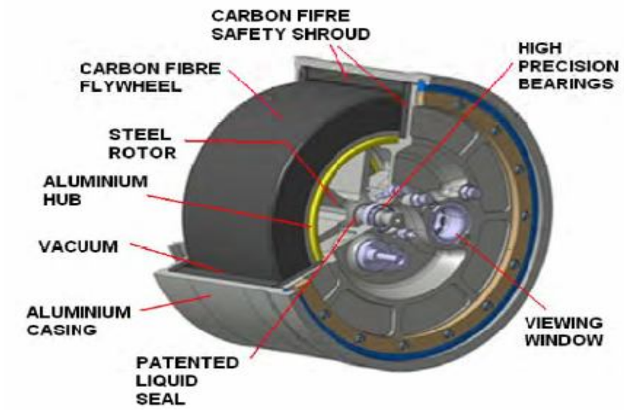


Figure 5. Inertial flywheel design by Flybird Systems for F1 racing [6].

SCHEMATIC DRAWING OF THE ANALYSED KERS

The schematic drawing of the analysed system is presented in Figure 6.

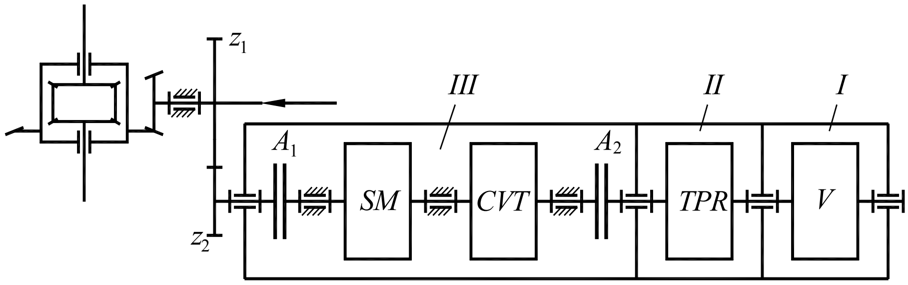


Figure 6. Working scheme of a KERS

The main element of a *KERS* is the flywheel *V* which can store and deliver mechanical energy. It is placed in a vacuum enclosure *I* for minimising air friction. The transmission of movement is made through a planetary transmission with rollers *TPR* which is located in an enclosure *II* which has a controlled environment. For creating this system a planetary transmission with friction rollers and gears was used due to the necessity of obtaining very high gear ratios ($i_1 = 100$) at very high efficiency ($0{,}98..0{,}99$) both for increasing and decreasing the gear ratio [2]. The transmission satellites are deployed on two or three rows so that the rollers are balanced sustained in three points. A solution like this simplifies very much the bearing system of the rollers, satellites and mobile wheel. In conformity with [2], this kind of system can transfer powers up to *800 kW* for a gear ratio $i_1 = 38$. For powers less that this the planetary transmission with rollers can have an input rotation speed of about *4,000 rpm* and an output rotation speed of about 480,000 rpm [2]. The connection/disconnection of the assembly *TPR –V* is made with the aid of the magnetic clutch A_2.

For rotation speed variation the dimmer *CVT* is used. This can be a roller dimmer or a planetary dimmer with two or three central wheels. Dimmers like this are used daily to create a large variety of rotation speeds in the interval $[0..0.4]\omega_{input}$.

For torque adaptation a mechanical system *SM* is being used which has the role to step or step down the torque coming from the engine with the gear ratio i_2. At the input, the system was designed with a connection clutch A_1 which has a safety role limiting the torque delivered by the engine.

The *KERS* is linked by the gears z_1, z_2 at the differential-drive pinion of the main transmission of the vehicle.

FLYWHEEL DYNAMIC ANALYSIS

The equation which describes the energy stored at flywheels level is:

$$T = \frac{1}{2} J_V \omega^2 [J], \tag{1}$$

Where: T is the energy in joules, J_V is the inertial modulus of the flywheel (kgm^2) and ω is the angular rotation speed (rad/s).
Considering the design from fig.7 for the flywheel, his mass is given by the relation:

$$m_V = \rho_V \pi \left(R_2^2 - R_1^2\right) L \; [kg], \tag{2}$$

where we noted with: ρ_V - flywheel's density , R_1 – inner radius, R_2 – outer radius, L – flywheel length.

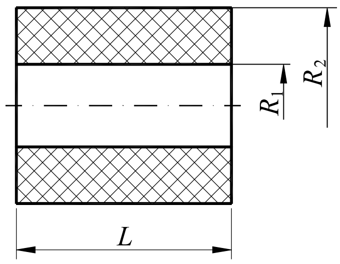


Figure 7. Building model of the flywheel.

The moment of inertial J_V of the flywheel from Figure 7 is given by the relation below:

$$J_V = \frac{1}{2} m_V \left(R_1^2 + R_2^2\right) [kg \cdot m^2]. \tag{3}$$

Replacing in the kinetic energy equation the expression of moment of inertia given by relation 3 we obtain:

$$T = \frac{1}{4} m_V \left(R_1^2 + R_2^2\right) \omega^2 \; [J]. \tag{4}$$

If we note with $\Delta t_{\min}$ the necessary time for the *KERS* to give up the stored energy we will find the peak power of the system P_{V-KERS} :

$$P_{V-KERS} = \frac{T}{\Delta t_{\min}} \; [W], \tag{5}$$

NUMERICAL APPLICATION

We consider the *KERS* equipped with a flywheel which has the design given by Figure 7. It is made from carbon fibre having a density $\rho_V = 2.720 \left[\text{kg/m}^3\right]$, the inner and outer radiuses: $R_1 = 0{,}050\,\text{m}$, $R_2 = 0{,}100\,\text{m}$ and the width $L = 0{,}073\,\text{m}$. In conformity with relation (2) we will determine the mass $m_V \cong 4{,}6785 \; [kg]$ and applying relation (3) we will find the moment of inertia $J_V = 0{,}02924 \; [\text{kg} \cdot \text{m}^2]$. At the maximum rotation speed $n_{V_{\max}} = 50.000$ rpm the flywheel will have an angular rotation speed

$\omega_{\max} = \frac{n_{V_{\max}} \pi}{30} = 5236$ [rad/s] .Thus at this angular speed we will have a stored energy $T = 400.820 \; [J]$ which in conformity with equation (5) will determine in a time $\Delta t_{\min} = 5{,}7\,\text{s}$ a maximum power $P_{V-KERS} \cong 70.320$ [W].

CONCLUSIONS

Featured in 2008 on the F1 cars, the KERS proved their utility and reliability. These systems were also used on concept cars in the 24 hours race of Le Mans [5]: in 2011 by the team Hope Racing, in 2012 and 2013 by companies like Audi, Toyota, Porsche and others.

Volvo is currently working on introducing in the shortest time a series vehicle equipped by *KERS* with inertial flywheels. Being a new system we will analyse the main advantages and disadvantages of these *KERS* with inertial flywheels.

Among the disadvantage we remind:

- at high rotation speeds any malfunction can lead to serious damage,
- the energy cannot be stored for a long time such in the case of batteries storage,
- the weight of the system leads to an increase of the fuel consumption.

The advantages of the system are mainly consisting of:

- the capacity of the system to store over 70 % of the total energy of the vehicle during the braking sequence,
- increased efficiency of system due to the fact that there is no conversion of the mechanical energy in another form of energy,
- reduction of maintenance costs by reducing brakes wear,
- reduction in fuel consumption and of costs in comparison with electrical hybrids and many others.

The vehicles equipped with inertial *KERS* are efficient in urban cycles when there are many starts and stops of the car. The tests made by Volvo with a vehicle equipped with inertial flywheel made by *Flybird Systems* proved that fuel consumption reduction can be up 20%.

As a conclusion we can say that inertial flywheel *KERS* represent a technology with an overwhelming potential from a point of view regarding costs and also performances.

The usability of these systems for the automotive industry will lead to the increase of hybrid vehicles efficiency, fuel consumption and emissions reduction and in the same time the increase of the propulsion system's power.

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