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Optimisation of flywheel energy storage systems with geared transmission for hybrid vehicles

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ABSTRACT

Flywheel energy storage devices may be coupled to mechanical transmissions for braking energy recovery and the provision of additional power for acceleration in hybrid vehicles. Power transmission across a continuous range of speed ratios is necessary. The flywheel size and depth-of-discharge must be chosen for a particular application, and this has a direct effect on transmission efficiency, required gearing ratios and mass of components. Optimisation of these parameters requires a fundamental understanding of this interaction, which has not previously been investigated and reported. To address this, the current paper presents a new method of analysing mechanical flywheel systems. A simple algebraic analysis can be used to specify flywheel system parameters for any regenerative braking application where the flywheel is used to provide initial acceleration of the vehicle from stationary. This has been applied to systems using geared transmissions with continuous speed variation achieved through sliding contact in clutch and brake components. The results of the analysis highlight how the optimum selection of flywheel depth-of-discharge must achieve a balance between high transmission efficiency and low system mass. This is illustrated for a passenger car application, allowing a full assessment of system performance and the specification of appropriate design parameters.

1. Introduction

Flywheel energy storage systems with mechanical transmissions allow regenerative braking and power augmentation during acceleration in automotive vehicles. The development of this technology is being driven by rising fuel costs and tightening emission legislation. In recent years the issue of climate change has generated great scientific and public interest in the effect of human activity on the The production of greenhouse gasses has been linked with global temperature rises [1], and in the light of reports such as the Stern Review on the economic impact of climate change [2] a general consensus appears to have been reached on the need to limit such emissions. Road vehicles account for a significant proportion of the total world energy use and energy-related CO_2 emissions, and stabilisation of atmospheric CO_2 concentrations is likely to require continuous improvements in vehicle efficiency over the next 40 years as mapped out by the IEA [3].

Many fuel saving technologies are currently available, but the associated increase in vehicle cost appears to be limiting widespread implementation. Power-train hybridisation is an attractive option for achieving significant fuel savings, especially when

Abbreviations: CGB, control gearbox; CST, continuous slip transmission; CVT, continuously variable transmission; DDC, dual differential coupled; FDC, final drive coupled; PGSplanetary gear set.

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Nomenclature

$\bar{E}$	specific energy capacity
$\overline{T}$	specific torque capacity
E	energy
G_j	general fixed gear ratio in CGB (where j has a value between 1 and N_{cgb})
J	moment of inertia
K	fixed gear ratio connecting CGB to PGS or vehicle final drive
m	mass
N	total number of PGSs in a transmission
N_{cgb}	number of fixed gear ratios in CGB
P	power
R_n	characteristic gear ratio of a general PGS in a multi-PGS brake controlled transmission (where n has a value between 1 and N)
R_p and R_q	characteristic gear ratio of general PGSs in a CGB controlled transmission
r_w	vehicle wheel radius
T	torque
V	velocity
η_n, η_p, η_q	efficiency of the corresponding general PGS
η_{trans}	instantaneous transmission efficiency
$\overline{\eta}$	mean transmission efficiency
λ	flywheel depth-of-discharge
ω	angular velocity

Subscripts

ch	relating to flywheel charging operation
cyc	relating to the charge–discharge cycle
dis	relating to flywheel discharge operation
f	final
fd	relating to final drive of vehicle
fw	relating to flywheel
i	initial
sys	relating to the total flywheel system
veh	relating to the vehicle

combined with other energy saving measures such as stop-start engine operation. However, even a simple mild hybrid system can add around 20% [3] to the cost of a typical passenger car, largely due to the high cost of electric motors and electrochemical batteries relative to conventional powertrain components. Several types of energy storage device are available for use in hybrid vehicles, and an initial indication of their suitability can be obtained from the Ragone plot [4], which shows the specific energy and specific power that can be achieved with different energy storage technologies. The more detailed analysis presented by Stewart et al. [5] shows how lithium-ion batteries and supercapacitors can be optimised for hybrid electric vehicle applications, where a discharge time of 10 s has been assumed. Ceraolo et al. [6] obtained similar results, but state that the power limitation of lithium-ion batteries occurs during charging where the current must be limited to avoid damage; for effective regenerative braking with a charging period of 10 s, the specific power was found to be only 16% of that achieved for discharging over the same period. In this case, the battery had a measured specific power (excluding packaging weight) of 330 W/kg, and charge–discharge efficiency of 85%, while the supercapacitor achieved around 720 W/kg and 87% respectively. The corresponding specific energy of these devices is in the region of 15–30 kJ/kg for the hybrid vehicle application [5]. It is important to note that the efficiency values do not include the additional losses that would occur in the electric motor and associated power control electronics of a vehicle during charge and discharge, and that the mass of these additional components and packaging will significantly reduce the specific power and specific energy of the system. There are also limitations to battery cycle life and difficulties with recycling the expensive materials used in modern high performance batteries. In recent years, flywheels have received considerable attention as an alternative to electrical energy storage that can potentially offer low cost and long operational life, and are discussed in more detail in the following section. In summary, it is clear that there is a compromise between improving specific fuel consumption and increasing the total cost of the vehicle which is highly dependent on the type of hybrid system and energy storage device used.