

Energy Recovery Efficiency of Flow-coupled Flywheel Vehicle

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Abstract: In this study a flow-coupled flywheel vehicle was proposed and its energy recovery efficiency was discussed. This new kind of flywheel vehicle has simpler configuration, fewer components and easier control method. And it was confirmed that this system had enough capability to recover vehicle kinetic energy that might otherwise be lost as heat during braking. Then, more attentions were paid to initial speed of recovery flywheel and displacement ratio of variable displacement pump/motor that influenced recovery efficiency of the proposed hybrid vehicle. Experimental results show that the maximum recovery efficiency will amount to about 82%. It is also significant to point out that in order to improve recovery efficiency, the displacement size of variable displacement pump/motor is required so as to make it operates as maximum displacement and the initial speed of the recovery flywheel is limited at a suitable scope (about 1000~3000 rpm) with regard to the windage and axial loss and the amount of energy storage. Hence, it is indicated that this type of hybrid vehicle can be as an optional configuration to widely use in hybrid vehicle.

Keywords: Displacement ratio, energy recovery efficiency, flow couple , flywheel vehicle, flywheel energy storage

INTRODUCTION

Many countries are examining a whole range of new policies and technology issues to make their energy futures 'sustainable'. That is, to maintain economic growth whilst providing energy security and environmental protection (Dell and Rand, 2005). Especially, it is strongly requested to reduce fuel consumption and exhaust gases from road vehicles for environmental preservation (Kawaguchi and Kiyoshi, 2006; Briat *et al.*, 2007). Hybrid vehicles which could recover vehicle kinetic energy that might otherwise be lost as heat during braking, were attractive from the viewpoint of energy saving (Briat *et al.*, 2007; Shen and Veldpaus, 2004). There are several ways to store kinetic energy such as an electrical battery, a rotary flywheel or a hydraulic accumulator (Hebner *et al.*, 2002). Hydraulic accumulator had small energy density and electrical battery has small power density (Fig. 1). Flywheel was proving to be an ideal form of energy storage on account of its high power and energy density, high efficiency, long cycle life, wide operating temperature range and freedom from depth-of-discharge effects (Liu and Jiang, 2007; Lawrence *et al.*, 2003). Now, flywheel hybrid vehicles had been developed because CPS (Constant Pressure System) avoided using complex and expensive CVTs (Continuously Variable Transmissions). Shinichi proposed a flywheel hybrid vehicle making use of CPS whose fuel consumption amounted to 26 km/L with mass of 1500 kg (Suzuki, 2005). A flywheel hybrid vehicle was proposed using switch type closed loop CPS to solve the pressure peak generated by the abrupt change of the hydraulic

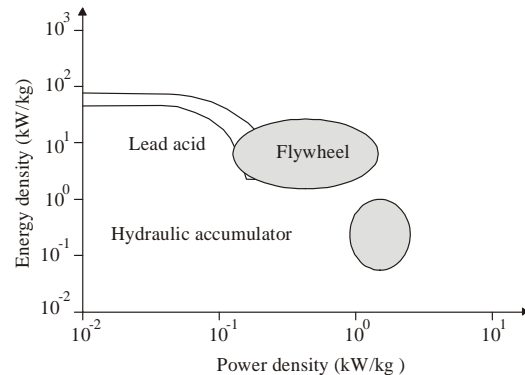


Fig. 1: Energy density vs power density of the compared energy storage units

pump/motor displacement (Ahn and Oh, 2005). However, the CPS had some problems such as complex configuration, expensive price of the variable displacement pump/motor and intricate control. In this study, a flow-coupled flywheel vehicle was proposed as an alternative energy saving method which simplified the vehicle configuration and control and reduced its cost. Then, attentions were paid to recovery efficiency in the proposed flywheel hybrid vehicle. Angular velocity of the flywheel and displacement of hydraulic pump/motor, as the important factors influencing its recovery efficiency, were discussed. Finally, experimental results show that the bigger the ratio between actual displacement and maximum displacement is, the higher the efficiency is. The efficiency is not proportional to the angular velocity

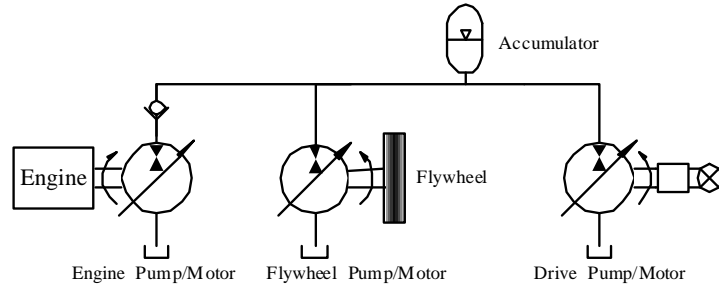


Fig. 2: Schematic diagram of flywheel vehicle using CPS

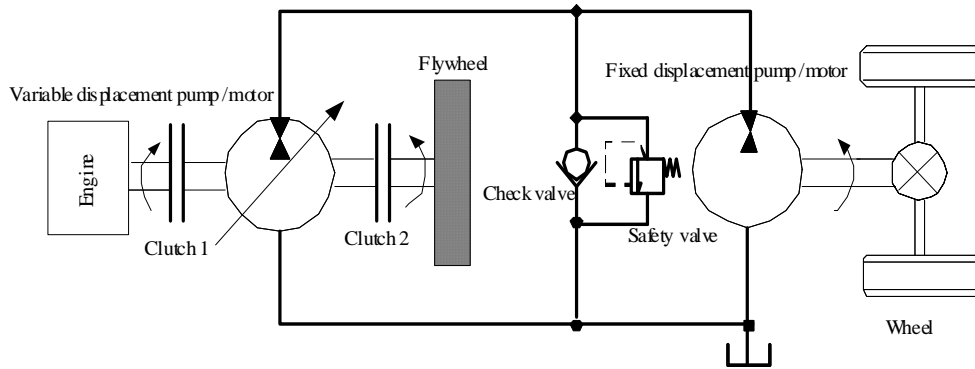


Fig. 3: Schematic diagram of flow-coupled flywheel vehicle

because windage loss will amount to large value when the angular velocity is over 2500 rpm. This study provides an option and is meaningful for wide use of flywheel vehicle.

FLOW-COUPLED FLYWHEEL VEHICLE

A schematic diagram of flywheel vehicle using CPS was shown in Fig. 2. This system consisted of a flywheel, three variable displacement pump/motors and a hydraulic accumulator. The flywheel pump/motor integrated with a hydraulic accumulator kept system operating constant pressure in this CPS. Both speed and torque of the vehicle were controlled by varying the displacement of the drive pump/motor. The drive pump/motor was used as a motor during the acceleration and as a pump during braking.

A schematic diagram of flow-coupled flywheel vehicle was shown in Fig. 3. This system consisted of a flywheel, a variable displacement pump/motor, a fixed displacement pump/motor and two clutches. The difference between the new system and that CPS system was that the proposed system was substituted a fixed displacement pump/motor (as drive pump/motor) for a variable displacement pump/motor and eliminated the hydraulic accumulator. And the system pressure would be changing with the drive and brake torque. When the drive

or brake torque was increasing, the system pressure would go up, vice versa. The speed of vehicle was controlled by regulating the displacement of the variable displacement pump/motor. The operation principle of the system was as follows:

- If clutch 1 was coupled and clutch 2 was coupled, Engine and flywheel drove vehicle together when the fix displacement pump/motor would be used as a motor and the variable displacement pump/motor as a pump. Here, the excess power being produced by the engine could be used to accelerate the flywheel speed to avoid dissipation. On the other hand, Flywheel could be used as an assistant power to help electromotor provide peak.
- If clutch 1 was coupled and clutch 2 was uncoupled, Engine drove vehicle individually when the fix displacement pump/motor would be used as a motor and the variable displacement pump/motor as a pump.
- If clutch 1 was uncoupled and clutch 2 was coupled, flywheel drove vehicle individually until the flywheel speed went down to the lower limit when the fix displacement pump/motor would be used as a motor and the variable displacement pump/motor as a pump.

- If clutch 1 was uncoupled and clutch 2 was coupled, vehicle was on condition of brake or descending mode and flywheel was accelerated due to recovering the kinetic energy of vehicle when the fix displacement pump/motor would be used as a pump and the variable displacement pump/motor as a motor.
- If clutch 1 was coupled and clutch 2 was coupled, flywheel could be accelerated so as to help engine to start vehicle when the fix displacement pump/motor was kept in the neutral position. The flow-coupled flywheel vehicle has simpler configuration, fewer components and easier control method due to using a fixed displacement pump/motor.

Key factors for energy recovery efficiency: There were two key problems to solve for flowed-coupled flywheel vehicle. One was how to allow the engine to be operated in the optimum operation efficiency point. The other was how to improve the energy recovery efficiency. This paper will focus the latter. The energy recovery efficiency was influenced by some parameters, such as rotational speed (angular velocity) of flywheel, displacement ratio of the variable displacement pump/motor (ratio between actual displacement and maximum displacement), pressure, temperature and so on. Meanwhile, the rotational speed and displacement ratio were the key factors to improve the recovery rate of potential energy.

Rotational speed of flywheel: The flowed-coupled flywheel vehicle efficiency depended strongly on the stand-by losses, which has close relationship with rotational speed of the flywheel. The kinetic energy quantity, E , stored in the rotating mass E can be calculated as follows:

$$\frac{dE}{dt} = I\omega \frac{d\omega}{dt} = T\omega \quad (1)$$

Torque coursed by rotating loss increased proportionally to the square proportion of rotational speed. And torque can be expressed as follows:

$$T = T_{ax} + T_{wind} = \mu\omega + b\omega^2 \quad (2)$$

where, I was the moment of inertia. T was the total torque loss. T_{ax} was axial friction torque, T_{wind} was windage friction torque. μ was the axial friction coefficient and b was the windage friction coefficient. Windage loss, P_{wind} , can be written as:

$$P_{wind} = 2C_{df} \rho R^5 \omega^3 \quad (3)$$

where, coefficient of air resistance: C_{df} , mixture gas density: ρ , rotor radius: R . therefore, recovery energy was

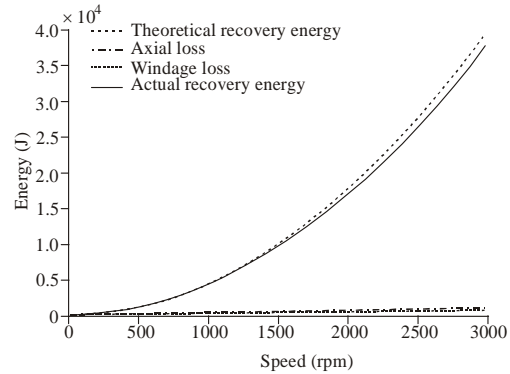


Fig. 4: Theoretical and actual recovery energy and windage & axial loss

Table 1: Specifications of the flywheel

Specifications	Value
Rotor mass, m (kg)	40
Rotor inertia, I (kg m ²)	0.8
Rotor radius, R (m)	0.2
Air density ρ (kg/m ³)	1.19
Coefficient of air resistance, C_{df}	3.24×10^{-3}

calculated by the difference between stored energy and windage loss:

$$E \frac{1}{2} I \omega^2 - \int 2C_{df} \rho R^5 \omega^3 + \mu \omega^2 \quad (4)$$

Supposed the specifications of a flywheel were shown in Table 1. In his way, the recovery energy, axial loss and windage loss could be obtained in Fig. 4. Figure 4 shows that the operation speed of a flywheel is very important regarding the efficiency (and the size of course). the higher the speed, the higher the loss (in energy percent), as the stored energy grows with the square of the angular velocity, but the windage and axial loss grows with cube and square angular velocity respectively. Hence the windage loss will account for around 6 percent of actual recovery energy if the angular velocity amounts to 3000 rpm.

Displacement ratio: In addition, the size of the variable displacement pump/motor should be considered. The basic equations describing pump/motor operation and efficiency were summarized in general equation format. Mechanical and volumetric efficiencies were inverted in going from operation as a pump to operation as a motor. The loss mechanisms described would contribute different amounts to overall efficiency relative to the pump/motor operating condition.

Theoretical Flow Rate: $Q = D_{p/M} \times \omega$
 Theoretical Torque: $T = D_{p/M} \times p$

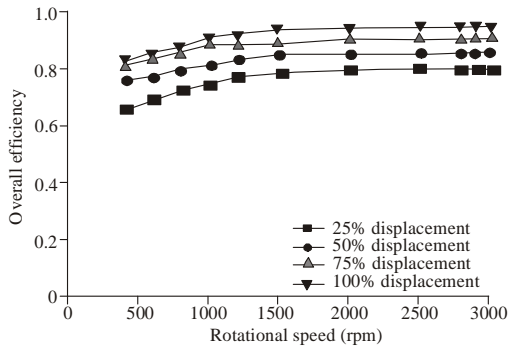


Fig. 5: Pump overall efficiency at different displacement ratio

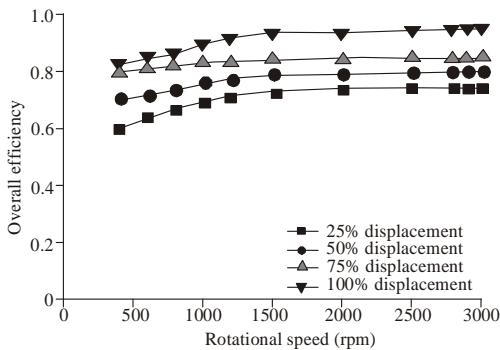


Fig. 6: Motor overall efficiency at different displacement ratio

Mechanical Efficiency: $\eta_M = T_{\text{actual}}/T_{\text{theoretical}}$
 Volumetric Efficiency: $\eta_V = Q_{\text{actual}}/Q_{\text{theoretical}}$
 Overall Efficiency: $\eta = \eta_M \times \eta_V$

where, ω is the rotational speed of the pump/motor and p is system pressure.

The volumetric efficiency was a function of Compressibility and leakage. Compressibility caused more reduction in volumetric efficiency to a pump than it done to a motor. At the same pressure, the volumetric efficiency was lower at lower speeds, this was because a

given leakage rate was a large fraction of the useful flow. When the speed is increased, the leakages become less significant. The mechanical efficiencies of the pump and motor were function of Coulomb friction and viscous friction. Coulomb friction was independent of speed, but viscous friction was dependent on speed. Viscous friction was increased as speed was increased. This caused a reduction in mechanical efficiency as speed was increased. The overall efficiencies of hydraulic pump/motor were the product of the volumetric efficiency and the mechanical efficiency. The overall efficiency was affected significantly by displacement ratio and was lower at lower displacements ratio as shown in Fig. 5 and Fig. 6. Figure 5 and Fig. 6 show the comparison of the overall efficiency respectively when functioning as a pump and motor at 100, 75, 50 and 25% maximum displacement.

Hence, a very small size providing a correspondingly small torque would have a high probability of being activated when the load was required to descend but in general would only recover a fraction of the potential energy available. On the other hand, a very large displacement providing a large torque would seldom be activated and lead to decrease its overall efficiency. In order to operate a pump/motor with acceptable overall speed is 1000 rpm efficiency, we have to choose a suitable displacement size of hydraulic pump/motor.

SIMULATION EXPERIMENTS OF ENERGY RECOVERY

An experimental set-up had been fabricated (Fig. 7). Maximum displacement of the variable displacement pump/motor $D = 4G10-5 \text{ m}^3/\text{r}$, displacement of the fixed displacement pump/motor $V = 4G10-5 \text{ m}^3/\text{r}$. the moment of inertia of load flywheel was the same with recovery flywheel. The other parameters were given in Table 1.

Simulation experiments were made to accelerate recovery flywheel due to recovering the kinetic energy of the load flywheel in case of different initial speed of recovery flywheel and different displacement ratio of the

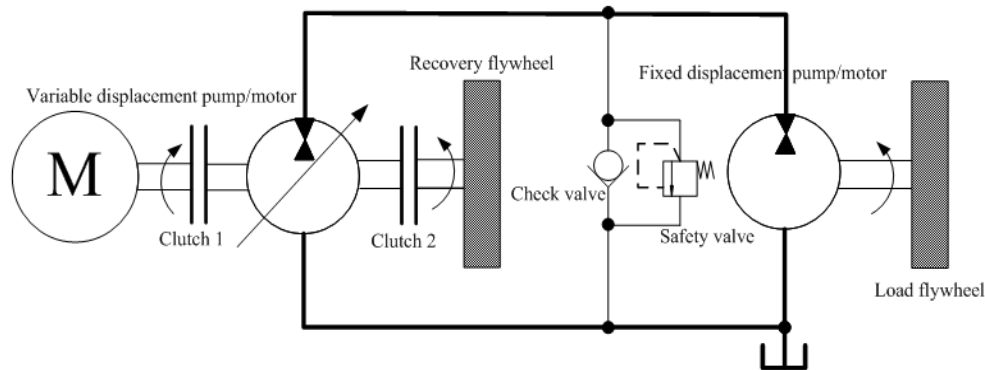


Fig. 7: Schematic diagram of the experimental set-up

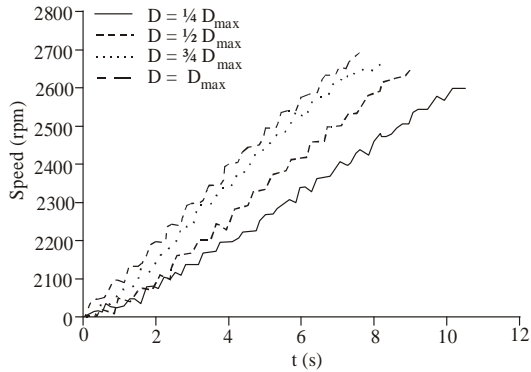


Fig. 8: Rotational speed of recovery flywheel when its initial speed is 2000 rpm

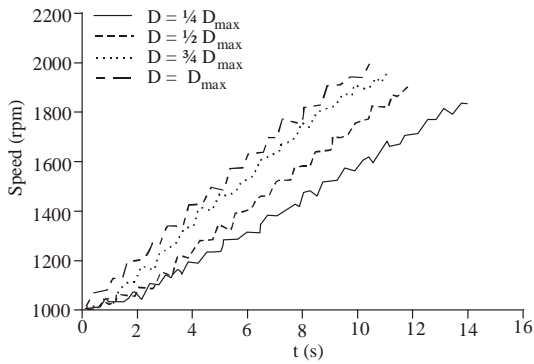


Fig. 9: Rotational speed of recovery flywheel when its initial speed is 1000 rpm

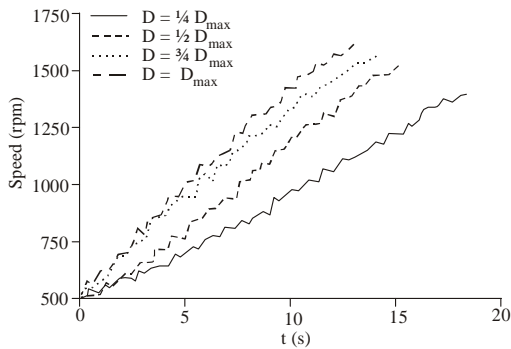


Fig. 10: Rotational speed of recovery flywheel when its initial speed is 500 rpm

variable displacement pump/motor when the initial speed of load flywheel was 2000 rpm. Figure 8, Fig. 9 and Fig. 10 show rotational speed of recovery flywheel when its initial speed is 2000, 1000 and 500 rpm, respectively and the displacement ratio of variable displacement pump/motor is 0.25, 0.5, 0.75 and 1, respectively. Figure 11 shows the recovery efficiency curve in the different initial speed of recovery flywheel when the displacement ratio is 1. Figure 12 plots therecovery efficiency for

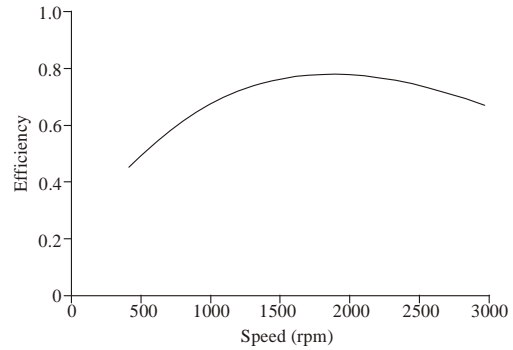


Fig. 11: Energy recovery efficiency at different maximum speed

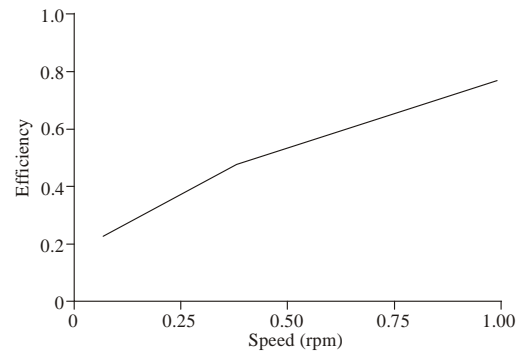


Fig. 12: Energy recovery efficiency at different displacement

different displacement ratio when the initial speed of recovery flywheel is 2000 rpm. Simulation experiments have revealed that the recovery efficiency is low at low initial speed and typically trends to increase to its peak (around 2500 rpm) and then decrease at high speed. However, the recovery efficiency augmentation is not obvious when the initial speed is more than 1000 rpm. And it is distinct that the efficiency is improved as the displacement ratio is increased, which is accordant to theoretical analysis. Although the overall efficiency of the pump/motor is proportional to the rotational speed, the windage and axial loss increase distinctly when the speed is over 3000 rpm. From the experimental results, the best energy recovery efficiency is 83.6% when $D=D_{max}$ and the recovery efficiency is remarkably worsened when the initial of recovery flywheel is lower than 500 rpm and the displacement ratio is less than 0.25. Hence, we can conclude that flywheel vehicle recovery efficiency will be improved in case that the variable displacement equals to the maximum displacement and the initial speed of recovery is more than 1000 rpm. The high initial speed is unfavorable taking account into storing more energy.

CONCLUSION

A new flywheel vehicle configuration (flow-coupled flywheel vehicle) was developed. It had simpler

configuration, fewer components and easier control method. And it was confirmed that this system had enough capability to recover vehicle kinetic energy that might otherwise be lost as heat during braking. From the theoretical and experimental study, the rotational speed of recovery flywheel and the displacement ratio of variable pump/motor were two key parameters for energy recovery efficiency. It was estimated that, in the proposed system, the maximum recovery efficiency will amount to about 83.6%. It was also significant to point out that in order to improve recovery efficiency, the displacement size of variable displacement pump/motor was required so as to make it operates as maximum displacement and the initial speed of the recovery flywheel was limited at a suitable scope (about 1000~3000 rpm) with regard to the windage and axial loss and amount of energy storage.

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