A Study on the Hydraulic Pump/Motor Control in the Flywheel Hybrid Vehicle

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Abstract: In this study, a novel hybrid vehicle is proposed. The vehicle has a flywheel-engine hybrid system. Flywheels are more effective as energy charge systems than electric batteries in a respect of output power density. However, transmissions to effectively drive flywheels are very complex systems such as CVTs (Continuously Variable Transmissions). In the proposed hybrid vehicle, Constant Pressure System is employed, which is hydraulic power transmission. Using Constant Pressure Systems, hydraulic CVTs are easily realized with variable displacement pumps/motors. In this paper, firstly, the proposed flywheel hybrid vehicle making use of Constant Pressure System is described. Secondly, fuel consumption characteristics of the flywheel hybrid vehicle are experimentally examined with the stationary test facility, which employs a flywheel as a load emulating vehicle inertia. Finally, the experimental results and discussions are described. Fuel consumption of 26km/L is expected for 10 mode driving schedule with vehicle mass of 1500kg.

Keywords: Fluid Power System, Hybrid Vehicle, Flywheel, Energy Saving, Constant Pressure System

1. INTRODUCTION

Recently, it is strongly requested to reduce fuel consumption and exhaust gases from road vehicles for environmental preservation. Hybrid vehicles, which recover vehicle kinetic energy that might otherwise be lost as heat during braking, are attractive systems from the viewpoint of energy saving. How to accumulate exhaust energy at braking is the most important technology for the energy recovery system. There are a lot of ways to accumulate kinetic energy, for example, an electrical battery, a rotary flywheel, a hydraulic accumulator(1)(2), etc. Among them, an energy recovery system using a rotating flywheel has been considered to be advantageous for the vehicle applications due to its high energy/power density. However, flywheel hybrid vehicles have not been developed for widespread use. Because a continuously variable transmission (CVT) between flywheel and drive wheels must be added to a conventional vehicle drivetrain, the flywheel energy recovery systems developed up to now becomes very complicated and costly. To solve this problem, the authors propose a Constant Pressure System (CPS) which is a simple hydraulic drive system for the engine flywheel hybrid vehicle, compared to the conventional transmission. CPS of which concept is similar to secondary control can realize power transmission and vehicle traction (acceleration/deceleration) controls easily.

In this research, it is realized CVT by using CPS system and purpose is that realizing flywheel hybrid vehicles as sub power unit. In former research(3)(4), examination by simulation was achieved. In the result, it is confirming that possibility of reducing fuel consumption at general city traveling.

In this paper, bench tester of flywheel hybrid vehicles using CPS system is manufactured, and examines character of fuel consumption experimentally. Furthermore, through comparison and consideration with simulation, examine possibility of flywheel hybrid vehicles.

2. FLYWHEEL HYBRID VEHICLES USING CONTANT PRESSURE SYSTEM

2.1 System configuration

Figure.1 displays composition of flywheel hybrid vehicles' driving mechanism using CPS. Engine and flywheel have been linked on equal axle and pump/motor is connected on each group. Here is, using variable displacement pump/motor is possible any operation of pump or motor. Accumulator is connected on common high pressure line to absorb pressure pulsation.

2.2 Operation principle of flywheel hybrid vehicle

CPS is a hydraulic power transmission system which consists of a flywheel and three variable displacement pump/motor's. Both driving and braking torque of the vehicle are controlled by varying the displacement of the drive pump/motor. The drive pump/motor is used as a motor during acceleration and as a pump during braking.

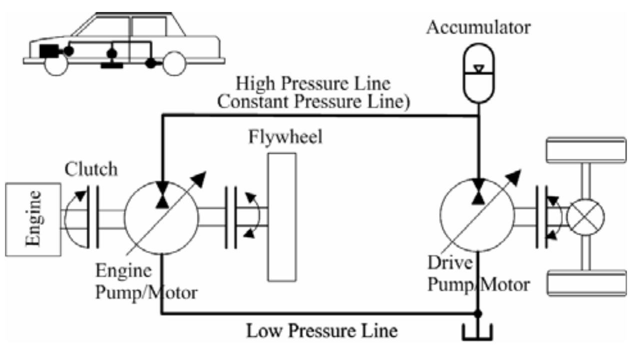

Fig. 1 Schematic diagram of flywheel hybrid car with Constant Pressure System

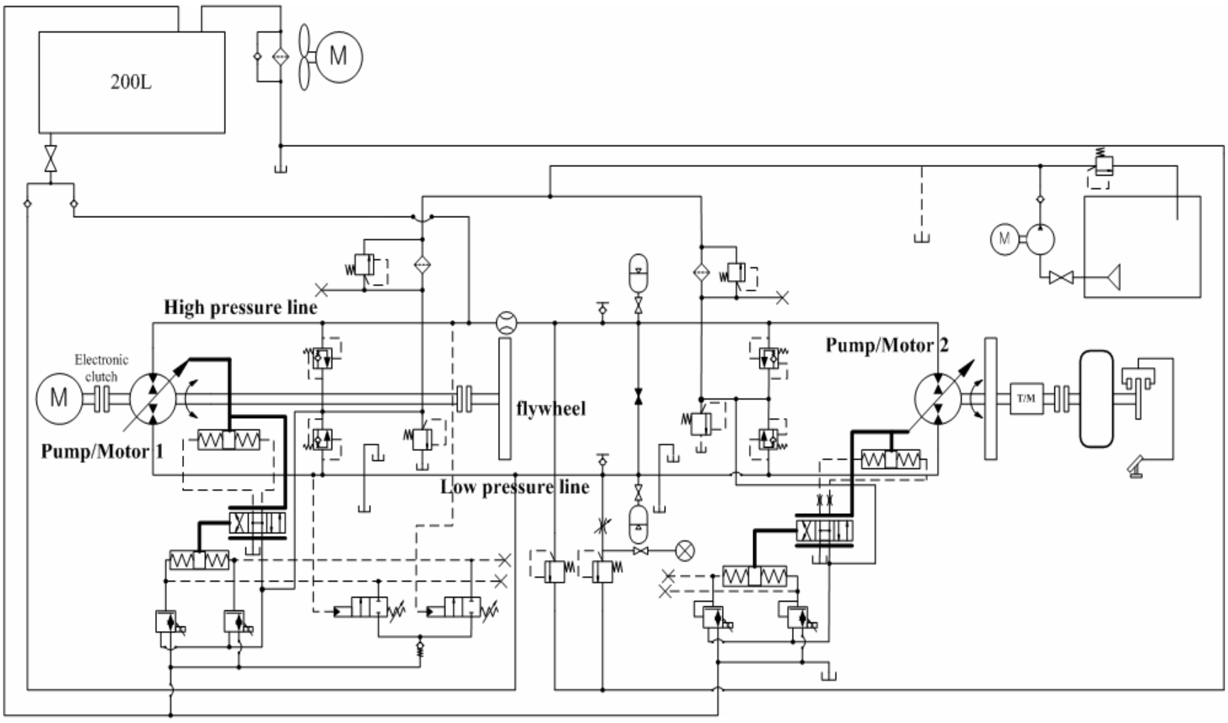

Fig.2 Hydraulic circuit of stationary test facility for flywheel hybrid car

The Flywheel pump/motor equipped with a pressure compensator operates to keep system operating pressure levels constant. When hydraulic energy of the system is consumed by the drive pump/motor and system pressure levels are going down, the engine pump/motor powered by the rotating flywheel discharges hydraulic fluid as a pump. When hydraulic energy is recovered by the drive pump/motor and system pressure levels are increasing, the engine pump/motor consumes hydraulic fluid as a motor and accelerates rotating speed of the flywheel. The Flywheel pump/motor namely functions as a constant pressure power source in CPS. Therefore the operation of the engine can be uncoupled from the speed and torque of drive wheels. It allows the engine to be operated at the optimum operating point, i.e., wide-open throttle independently of the power required by the drive pump/motor. The excess power being produced by the engine pump/motor can be used to accelerate the flywheel speed.

Thus the strategy of the engine operation in CPS is ON-OFF cycling. The engine is operated at the most efficiency point constantly, until the flywheel speed reaches the allowable upper limit. Then the engine is shut off and the vehicle is driven by the power produced by the flywheel pump/motor alone, until the flywheel speed goes down to the lower limit.

3. BENCH TESTER OF FLYWHEEL HYBRID VEHICLES

3.1 Construction

Fig.2 displays bench tester of flywheel hybrid vehicles' driving system. This experiment is expressing engine's energy supplying by hydraulic power unit and electronic valve. pump/motor. Both of pump/motor 1 and pump/motor 2 are using variable displacement pump/motor of FFC[(7)](Fluid Force Couple) type. Variable displacement pump/motor of FFC type has excellent character that is high efficiency in wide operating range, is suitable as pump/motor of hybrid vehicles. Maximum capacity is 49cc/rev, displacement is controlled by servo valve. Maximum speed of revolution is 524 rad/s (5000rpm).

Flywheel had connected to pump/motor 1 and pump/motor 2 was manufactured by duralumin and it's size is 500mm*60mm (moment of inertia 1.05kgm^2). If maximum speed of 1500kg's revolution is 524rad/s (5000rpm), maximum storage energy of flywheel becomes 144kJ and this is fair in kinetic energy that vehicles is driving by 14m/s(50km/h). Also, to keep away pump/motor's breakdown by cavitations using transformer 1MPa's boost pressure is done. Furthermore, to reduce pulsation of pressure in high and low pressure line, accumulator (10L,1L) has been established.

3.2 Vehicles' mass

From drive pump/motor this vehicle's equivalence moment of inertia I_d can saved from following equation (1) in Fig.1.

$$I_d = \frac{MR^2}{\gamma^2} \qquad (1)$$

Only, M : vehicle's mass, R : radius of tire, g : reduction gear ratio, are displaying each. Here, if standard vehicle is considered (M = 1500kg, R = 0.28m, g = 5.8), flywheel's moment of inertia is 3.5kgm^2 and corresponds to 0.3times of an standard vehicle.

4. IMITATION EXPERIMENT METHOD OF CITY DRIVING

4.1 Driving schedule time

Efficiency of pump/motor influences greatly in hydraulic system that transfers energy by pump/motor. Also, variable displacement pump/motor depends greatly on displacement ratio (ratio about maximum displacement). Therefore in case achieve experiment of city driving of flywheel hybrid vehicles in circuit of Fig.2, it is important that doing capacity change of variable displacement pump/motor such as actual driving. In addition, because pressure of high pressure line is fixed, it is same effect that doing capacity change is equally fixed and doing output torque of pump/motor is equally fixed. As explain in front, in point that inertia moment of flywheel as inertia of vehicles is 0.3times of inertia of actual vehicles, angular acceleration of drive pump/motor becomes 0.3times to do output torque with actual situation. Therefore, times that reach in some angular velocity (the vehicles speed) become 0.3times of actual driving. On this account, it can evaluate system in near condition to actual vehicles by doing time axis 0.3times of actual vehicles driving schedule.

4.2 Displacement control method of flywheel pump/motor

Three CPS models are introduced in this study. The first model called CPS model A in this paper is a basic CPS model in which the displacement of the flywheel pump/motor is controlled by means of P-control. The second model called CPS model B in this paper is a model which is intended to improve the efficiency of energy recovery. In CPS model B, the displacement of the flywheel pump/motor is controlled by means of ON-OFF control. And the accumulator volume of CPS model B has a clutch which disconnects the flywheel from the pump/motor in order to reduce mechanical rotating loss when it does not work. In CPS model C the displacement of the flywheel pump/motor is controlled by means of p-control with hysteresis. Each parameter is decided as following in Fig.3, consulting simulation result that base on mathematics model of system, considering fuel consumption, pressure change of high pressure line, cavitations.

$$\Delta P_a = 3\text{MPa}$$
$$\Delta P_b = 2\text{MPa}$$
$$\Delta P_{c1} = 2.5\text{MPa}, \Delta P_{c2} = 0.5\text{MPa}$$

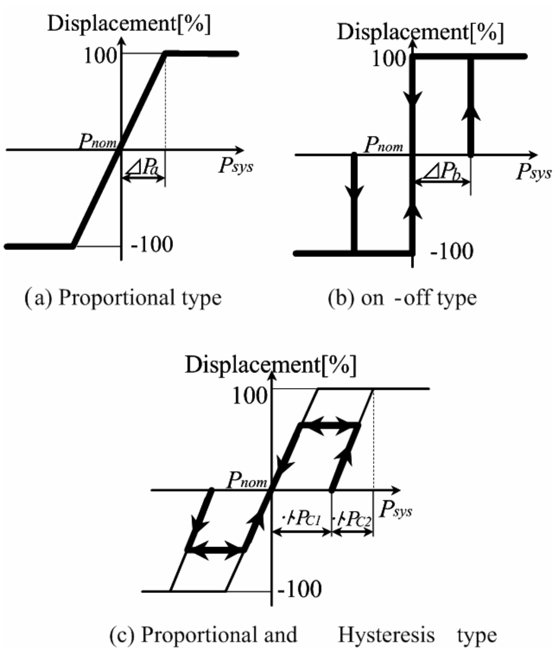

Fig.3 Control method of flywheel pump/motor displacement

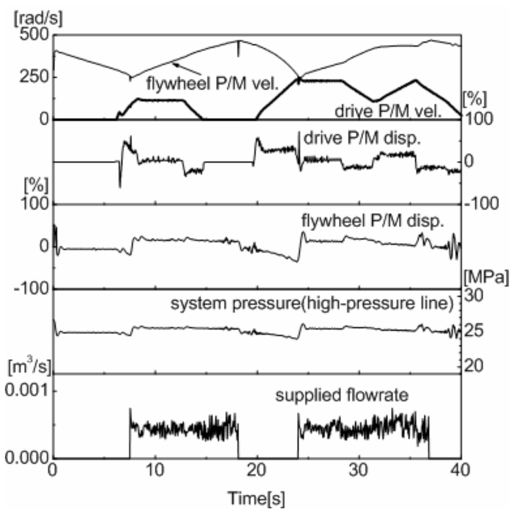

Fig.4 Experimental results of 10 mode urban driving schedule with proportional type

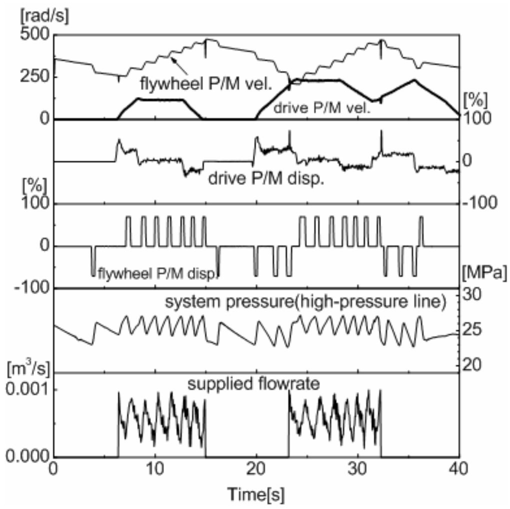

Fig.5 Experimental results of 10 mode urban driving schedule with on-off type

4.3 Calculating method of fuel consumption

Fuel consumption is supposed 230g/kWh in best condition. And fuel consumption ratio of engine calculates driving fuel consumption of flywheel hybrid vehicles. Fuel consumption ratio 230g/kWh referenced fuel consumption ratio map of actual 1800cc gasoline. Because experiment is doing by 0.3times time axis of driving schedules of actual vehicles, mileage is evaluated by driving 0.3times of actual vehicles' mileage (664m in 10mode) as 4.1. In experiment of city driving, spent energy E_c is produced by next following equation.

$$E_C = \int_0^t P_{High} Q_{Ps} dt - \frac{1}{2} J_{Fw} (\omega_{End}^2 - \omega_{Start}^2)$$

Here is, P_{High} : pressure of high pressure line, Q_{Ps} : flow of hydraulic power unit, J_{Fw} : inertia moment of flywheel, $\omega_{Ev\delta}$: angular velocity of flywheel pump/motor of experiment's ending, ω_{Start} : angular velocity of flywheel pump/motor of experiment's starting, t: time.

5. EXPERIMENT RESULT & CONSIDERATION

5.1 Experiment result

Fig.4~6 displayed simulation result of 10mode city driving by each proportional method of Fig.3. Certain case, component parts of pump/motor1, pump/motor 2, hydraulic power unit, etc. is doing each function, can know that copying of operating system of flywheel hybrid vehicles is coming true. Also, can know that copying of 10mode city driving is coming true from the wave form of rotation speed of drive pump/motor. Comparing the pressure pulsating of high pressure line in Fig.4~6, can know that proportional control of Fig.4 is most stable. On the other hand, in case of Fig.5's on/off control, can know that pressure of high pressure line is pulsating drastically. In proportional control with hysteresis of fig.6, pressure change of high pressure line is middle of proportional control and on/off control. Fig.7 is displaying the result of fuel consumption calculating in 10mode's city

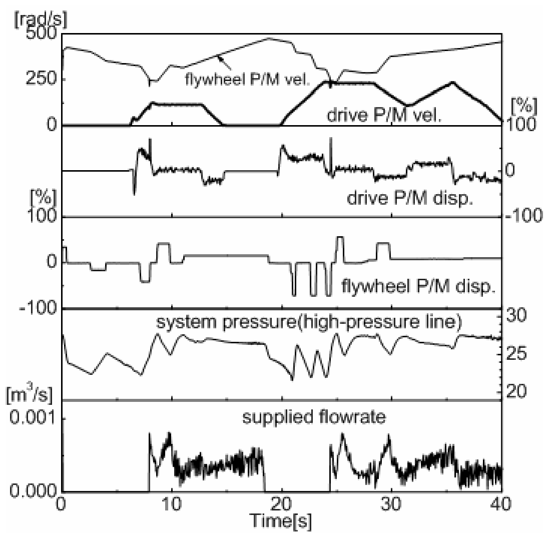

Fig.6 Experimental results of 10 mode urban driving schedule with proportional and hysteresis type

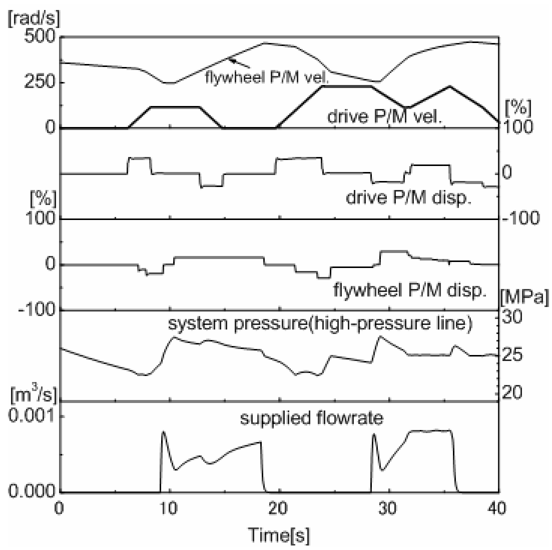

Fig.8 Simulation results of 10 mode urban driving schedule with proportional and hysteresis type

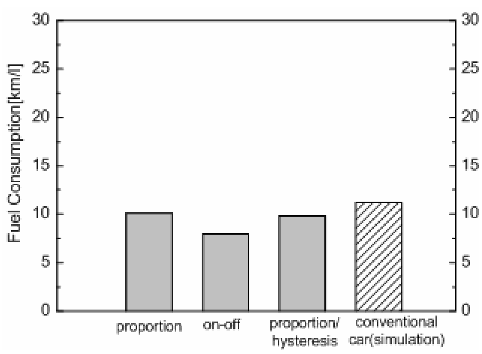

Fig.7 Fuel consumption of 10 mode urban driving schedule (experiment）

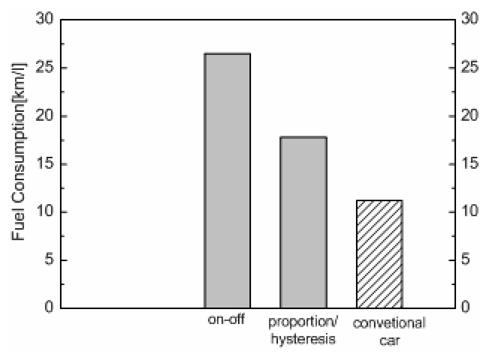

Fig.9 Fuel consumption of 10 mode urban driving schedule with clutch (simulation)

driving experiments of Fig.4~6. Also, fuel consumption of conventional vehicles using same engine for comparison appears together. The fuel consumption result such as conventional vehicles were obtained in proportional control and proportional control with hysteresis. Lower fuel consumption than conventional vehicles were obtained in on/off control. This result is thought that the loss, when displacement is zero, is the very important cause in flywheel pump/motor. Because energy recovery is consisting, calculating of transfer efficiency of manufactured bench tester is difficult. For reference, if transfer efficiency is calculated by following equation, it becomes 23%.

$$\varepsilon = \frac{E_C}{E_S} \times 100$$

Here is, E_S : energy that hydraulic power unit transfers to system, E_C : energy that flywheel gets, ε : transfer efficiency. 23% as transfer efficiency is low result. However, fuel consumption valuation of Fig.7 is same result with conventional vehicles. This is, character of flywheel hybrid vehicles, the reason that the engine is operating intermittently in good condition of engine efficiency and energy recovery.

5.2 Consideration about simulation

As explain 5.1 sections, it is expected that friction loss of pump/motor is influencing in fuel consumption. Connecting clutch between flywheel and pump/motor, in case capacity is zero, by separating flywheel and pump/motor, it is examined simulation about fuel consumption in case of removing friction loss. The result is displayed in Fig.9. By using mathematics model in simulation, Fig.8 displays an example of the result of 10mode simulation equally with an experiment. It agrees almost with experiment result of Fig.6 of equal condition. And it can confirm validity of mathematical model that used in simulation. From the result of Fig.9, big elevation of fuel consumption is expected as setting up clutch between flywheel and pump/motor.

6. CONCLUSION

In this paper, it is applied in sub power unit of flywheel vehicles as compounding new concept CPS of hydraulic system, variable displacement pump/motor and flywheel. Bench tester of driving system of flywheel hybrid vehicles is manufactured. Furthermore, by using manufactured bench tester, it is examined fuel consumption of expected flywheel hybrid vehicles in actual vehicles. Obtained important results are same as following,

(1) In control method of displacement of flywheel pump/motor, proportional control with hysteresis could be confirmed from simulation result that is expected good character, comparing to control method of the other 2, in all of change of system pressure and fuel consumption.

(2) The clutch is an important element about fuel consumption in flywheel unit of sub power unit. To introduction of the clutch, about 26km/L's fuel consumption is expected.

In an experiment, it could not obtain fuel consumption that exceeds conventional vehicles. Further studies are verifying the effect by experiment, and making clearly driving operation of vehicles etc.

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