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Design of a Parallel Hybrid Vehicle Powertrain with Semi-Spherical CVT

구면무단변속기를 적용한 병렬형 하이브리드차량 동력전달계 설계

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주요 용어 : 구면무단변속기(Semi-Spherical CVT), 하이브리드차량(Hybrid Vehicle), 동력전달계(Powertrain), 연결기어(Connecting Gear), 동력성능실험장치(Power Test Bench), 시작품(Prototype)

요 약 : 구면무단변속기(SS-CVT)는 구조가 간단하여 변속기구의 부피와 무게를 기존의 변속기구에 비하여 줄일 수 있으며, 별도의 클러치 없이 출력축의 정회전, 역회전 그리고 중립상태 등을 구현할 수 있다. 본 연구에서는 이러한 구면무단변속기의 기구적 특징과 변속메카니즘을 이용하여 직류모터와 가솔린엔진을 장착한 병렬형 하이브리드차량의 동력전달계를 제안하고자 한다. 이를 위하여 먼저 구면무단변속기의 작동원리에 대해 설명하고 전용 실험장치를 제작하여 무단변속성능을 검증하였다. 또한 직류모터를 보조 동력원으로 사용하는 병렬형 하이브리드차량 동력전달계의 설계를 위해 연결기어비와 구면무단변속기의 변속비를 차량주행성능에 맞추어 설정하였으며, 이를 차량가속성능의 수치 시뮬레이션을 통하여 분석하였다. 시뮬레이션 결과를 바탕으로 구면무단변속기의 하이브리드차량 동력전달계의 적용가능성을 검증하였으며, 연구결과로 선정된 구성요소의 설계파라미터를 이용하여 시작차량을 제작하였다.

Nomenclature

ω : angular velocity [rad/s]
θ : angle [rad]
I : mass moment of inertia[kg m^2]
R, r : radius [m]
a, b : gear ratio
T : torque [Nm]

1. Introduction

The hybrid electric vehicle (HEV) has continued to be an object of considerable research interest within the mechanical design community, driven primarily by the automotive industry's demands for more energy efficient and environmentally friendlier vehicles. According to the structure, HEVs can be classified into serial and parallel type vehicles. In a serial type HEV, the engine is connected to the generator and produces only the power for generating the electric energy into the driving motor and battery pack, and the electric motor produces the power for running a vehicle. Therefore, the structure and control strategy can be simple for serial HEVs, though the overall power efficiency is generally low for frequent energy transformations in power transmission.

Unlike the serial HEV, the engine in parallel HEV is connected to the drive shaft through the transmission which is also connected by the electric motor. Thus it is possible for the engine and electric motor both or separately to run the vehicle, and the engine power can be stored into the electric energy of battery pack by operating the motor as the generator. The power efficiencies of parallel HEVs are normally better than the serial ones because power transformation occurs less, and the driving power can be

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supplied by two sources. However the control strategies and hardware structure of the parallel HEV are complicate. Moreover in order to enhance the fuel economy and low emission, many parallel HEVs adopt the continuously variable transmission (CVT) in their drivetrains.

Unlike conventional transmissions (e.g., automatic and manual transmissions), in which the transmission ratio cannot be varied continuously due to fixed gear ratios, a CVT has a continuous range of transmission ratios that can, up to device-dependent physical limits, be selected independently of the transmitted torque. This feature of the CVT allows for engine operation at the optimum fuel consumption point consistent with the given output power requirements, thereby improving the engine's energy efficiency. Moreover, unlike conventional stepped transmissions the CVT does not suffer from "shifting".

According to the type of power transmission and shifting mechanism, existing CVTs can be classified into belt-type, traction drive, and hydrostatic/dynamic type[1]. In the previous study[2], a new type of CVT, the semi-spherical CVT (SS-CVT) is reported. The SS-CVT is marked by its simple kinematic design, improved efficiency of the shift actuator, and IVT characteristics, i.e., the ability of smooth transition between the forward, neutral, and reverse states without the need for any brakes or clutches. Because the SS-CVT transmits power via rolling resistance between metal on metal, it has limitations on the overall transmitted torque, which is effectively determined by the static coefficient of friction and the magnitude of the normal forces[3)~8)].

In this paper we present the design and analysis of the parallel HEV equipped with SS-CVT, together with experimental results of SS-CVT's performance. Section 2 describes the basic kinematic structure and operating principles of the SS-CVT. In Section 3 we show experimental results on the actual transmission ratio and power efficiency obtained with a hardware prototype of the SS-CVT. Finally we present the design of the parallel HEV prototype equipped with the SS-CVT. In addition, we investigate the accelerating performance of the prototype vehicle numerically.

2. Design of a semi-spherical CVT

2.1 Structure

The SS-CVT is composed of a set of output discs and variators. The output discs transmit power from the variators to the output shafts via dry friction force between the discs and the variators. And the semi-spherical variators are connected to the power source through a set of bevel gear (see Fig. 1). The variators are also connected to the shifting controller, and constrain the contact point with the output discs to be tangent to the rotational axis of the variator.

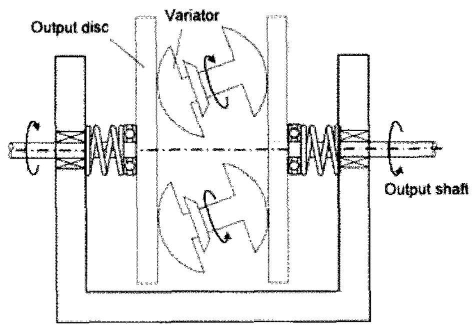


Fig. 1 Structure of SS-CVT

The speed and torque transmission ratios of the SS-CVT vary with the angular displacements of the variators; this will be described in further detail in the following subsection on the operating principles of the SS-CVT. To transmit power from the variators to the discs, a device that supplies a normal force to the discs, such as a spring or hydraulic actuator, must be installed on each shaft. As can be seen in Fig. 1, the structure and components of the SS-CVT are simple enough to allow for a considerable reduction in size and weight compared to conventional transmissions.

2.2 Operating principles

When the input bevel gear is rotated by a power source, the variator rotates about its spinning axis with the angular velocity of w_v (see Fig. 2). This rotation in turn causes a rotation of the output disc, due to the friction mechanism on the contact points between the output discs and the variators.

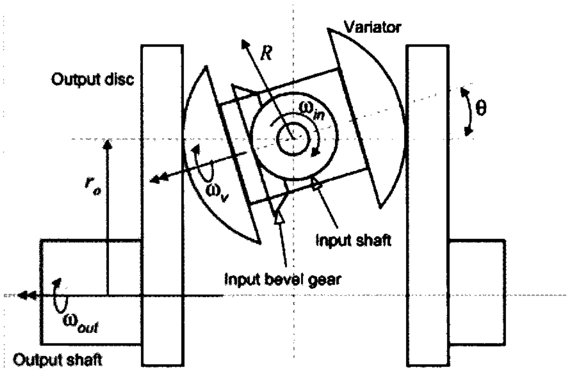


Fig. 2 Schematic diagram of SS-CVT

The role of the variator is to control the rotational speed of the output disc. By adjusting the axis of rotation of the variator into q, it is possible to vary the radius of rotation of the contact point between the output disc and the variator by the amount of $R\sin q$, where R is the radius of variator. In this way the speed-torque ratio of the SS-CVT can be adjusted. Fig. 3 shows the various alignments of the variator for the forward, neutral, and reverse states of the output shaft of the SS-CVT. The neutral state, which corresponds to zero rotation of the output disc, is achieved when variator angle q becomes zero. As apparent from the figure, the forward, neutral, and reverse states can all be achieved by smoothly manipulating the variator alignment, without the need for any additional clutches or brakes.

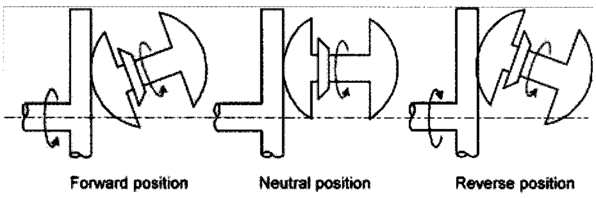


Fig. 3 Operating principles of SS-CVT

Assuming roll contact without slip, the speed ratio between the variators and output discs is related to the variator angle by the following relations:

$$\frac{\omega_{out}}{\omega_{in}} = \frac{R}{r_o}\frac{1}{\alpha}\sin\theta \tag{1}$$

where q is the angular displacement of the variator, w_{in} and w_{out} are the respective angular velocities of the input and output shafts, a is the gear ratio of input bevel gear set, and r_o is the radius of the output discs (see Fig. 2).

Although ideally an infinite torque ratio is possible with the SS-CVT, in practice there is a limit to the torque that can be transmitted because power transmission occurs from friction force. The limiting torque is determined by the static coefficient of friction and the normal force exerted by the output disc spring mechanism on the variator. When either the input or output torque applied at the disc-variator contact exceeds this limit, slippage can occur.

3. Experimental results of SS-CVT

In order to validate the operating principles and performance of the SS-CVT, we have built a prototype and test bench for it (see Fig. 4). The power capacity of the prototype is designed to be 11kW and the maximal input speed be 2500rpm. Two eddy-current type AC servo motors (output: 1100W; rated speed: 2500rpm) are used for a driving power source and a driven load generator. The input and output rotational speeds of prototype is measured by using optical encoders.

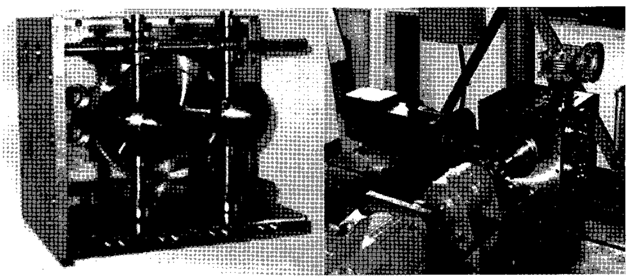
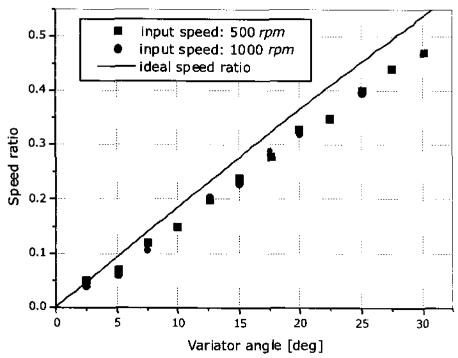
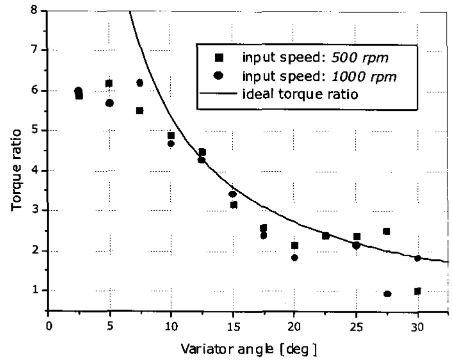


Fig. 4 Hardware prototype and test bench

Setting the external load torque to zero, we observe the output speed together with the variator angle displacement while the input speed is set respectively to 500 and 1000*rpm*. A steady-state speed ratio curve of the SS-CVT is extracted for the no-load condition (see Fig. 5 (a)). There is a large deviation between the ideal value and the test result beyond a variator angle of 20°, which indicates the onset of slippage. Using slip-ring type torque sensors, we have also observed the output torque together with the variator angle displacement by adjusting input/output torque to realize the pre-obtained steady state speed ratio (see Fig. 5 (b)). The actual torque ratio is limited to under 6, which is determined mainly by the static coefficient of friction and the exerted normal force.



(a) Speed ratio



(b) Torque ratio

Fig. 5 Experimental results of SS-CVT performance

4. Design of a parallel HEV

In this section, we present the design of an SS-CVT equipped parallel HEV, including numerical results on its power performance. The structural layout of the prototype vehicle is shown in Fig. 6.

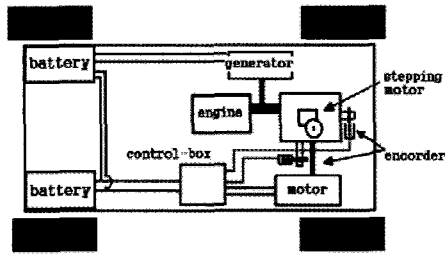


Fig. 6 Structure of prototype HEV

4.1 Prototype design

We have set the following performance targets to the prototype vehicle:

1) a top speed of 60*km/hr*;
2) a maximum ascending angle of 10°.

The engine is 125*cc*-2 stroke gasoline engine, which has the rated power of 125*kW*. The maximal power of the engine is 6.9*kW* at 10000*rpm*, and the maximal torque of 7*Nm* at 7000*rpm*. The specifications of prototype vehicle is shown in Table 1.

Table 1 Specifications of prototype HEV

Parameter	Value
Wheelbase	2.3 *m*
Full width	1.6 *m*
Overall height	1.1 *m*
Curb weight	400 *kg*

The prototype vehicle is designed to use only an electric motor during launching period, from the standstill until the vehicle speed reaches 5*km/hr*. When the vehicle starts to move, it is generally required for the power source to produce more torque than normal driving conditions; the necessary power capacity of the motor increases. Therefore we use an additional gear set, which connected to the motor and SS-CVT; the necessary motor capacity can be reduced. Assuming the time that the vehicle reaches 5*km/hr* as 1*sec*, we selected a 2*kW* DC motor (stall motor torque 130*Nm* at 147*rpm*) and the gear ratio of the connecting gear as 2 by calculating the load torque during the launching period.

From the above hardware specifications and structural layout, we have built the prototype vehicle (see Fig. 7).

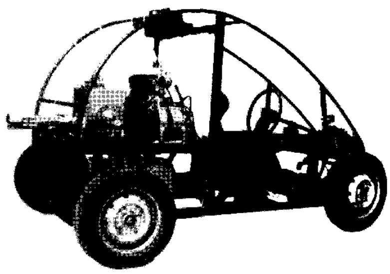


Fig. 7 Photo of prototype HEV

4.2 Numerical results on performance

In this subsection, we perform a numerical investigation of the accelerating performance of the SS-CVT equipped parallel HEV, in order to confirm the effectiveness of it. We now consider a schematic diagram for the numerical models of the prototype vehicle like Fig. 8. The equation of motion is derived as follows:

$$[I_{CVT} + I_{engine}(\frac{R}{d\sin\theta})^2 + I_{motor}\beta^2 + I_{vehicle}]\dot{\omega}_{out} = T_{engine}(\frac{R}{d\sin\theta}) + T_{motor}\beta - T_{load} \quad (2)$$

where, b is the gear ratio of connecting gear, w_{out} the angular speed of output shaft, and T_{engine}, T_{motor}, T_{load} are the produced torque of engine, motor, and load respectively, and I_{engine}, I_{CVT}, I_{motor}, $I_{vehicle}$ are moments of inertia of engine, CVT, motor, and vehicle respectively.

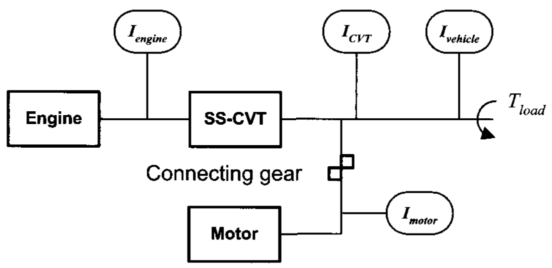


Fig. 8 Schematic diagram of prototype HEV

Based on the numerical models, we developed a simulation program. The driving conditions, used in the driving simulation, are as follows:

1) The engine is idling, when the simulation begins.

2) The end condition of the simulation is when the vehicle reaches 60*km/h*.

3) During the launching period (i.e., the vehicle speed reaches 5*km/h*), the prototype vehicle runs only by the electric motor.

4) After the launching period, the engine runs the vehicle with full throttle, while the electric motor does not operate;

5) The variator angle of SS-CVT changes continuously from 3.6°: the corresponding gear ratio that the engine speed of 800*rpm* meets with the vehicle speed of 5*km/h*.

The numerical results of SS-CVT gear ratio and vehicle speed are shown in Fig. 9. In this figure, the SS-CVT gear ratio changes from 16.8 to 5.7 during the simulation period. The duration time for the vehicle speed to reach 60*km/hr* is almost 20 seconds. In addition, Fig. 10 shows the corresponding speeds of engine and electric motor. The engine speed rises from 800 to 3500*rpm* until the simulation time becomes 13 seconds. And after that, the engine speed does not grow while the vehicle speed increases because the SS-CVT changes the gear ratio continuously. The increase of the electric motor speed is resulted from that the motor shaft is connected with the vehicle output shaft via SS-CVT, though the motor does not produce driving torque after the launching period.

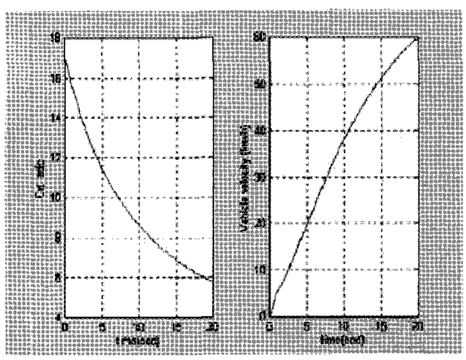


Fig. 9 SS-CVT gear ratio and vehicle speed

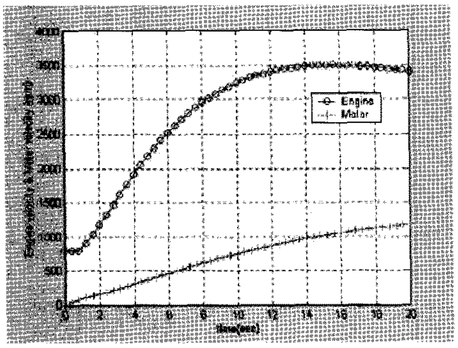


Fig. 10 Engine and motor speed

5. Conclusion

In this paper we presented the design and analysis of the parallel HEV equipped with SS-CVT, together with experimental results of SS-CVT's performance.

The SS-CVT is marked by its simple kinematic design, improved efficiency of the shift actuator, and the ability of smooth transition between the forward, neutral, and reverse states without the need for any brakes or clutches. Because the SS-CVT transmits power via rolling resistance between metal on metal, it has limitations on the overall transmitted torque, which is effectively determined by the static coefficient of friction and the magnitude of the normal forces. In addition, we have shown experimental results on the actual transmission ratio and power efficiency obtained with a hardware prototype of the SS-CVT. From the experimental results, we assessed the operating principles and CVT features of SS-CVT. The overall efficiency of SS-CVT is almost 78%.

Finally we presented the design of the parallel HEV prototype equipped with the SS-CVT. The hardware specifications of each component are designed based on the driving conditions and numerical results of the accelerating performance of the prototype vehicle. The numerical results show that the speed of prototype vehicle reaches 60*km/hr* in 20 seconds.

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