A new type compositive hybrid power system-E.T.Driver and its application in HEV

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Abstract: Hybrid power system is one of the kernel technologies of hybrid electric vehicles (HEV). The performance of HEV is greatly determined by the capability of hybrid power system. The hybrid power system has already developed from discrete structure into integrative structure in past ten years. The research of compositive hybrid power system is a very important and a new research field now and in the future. The Electrical Transmission Driver (E.T.Driver) is a compositive hybrid power system. The basic principle, constitution and the characteristics of E.T.Driver, which is based on Automatic Mechanical Transmission (AMT), have been introduced. The effect of E.T.Driver on gear shift quality, driving smoothness and riding comfort for HEV has been studied during gear shift course. A simulation model to analyze the gear shift application and gear shift strategy of E.T.Driver during gear shift course in HEV has been established by using the simulation software of ITI Company in Germany. The results of simulation and experiment show the proposed control strategies and special structure of E.T.Driver greatly improve the gear shift quality and driving smoothness during the gear shift course.

Key-Words: electrical transmission driver (E.T.Driver); hybrid electric vehicles（HEV）; gear shift quality; driving smoothness; modeling

1 Introduction

One of the kernel technologies of HEV is hybrid power system. The capability of hybrid power system will determine the whole vehicle performance of HEV directly. The hybrid power system has already developed from discrete structure into integrative structure in the past ten years. The integrative structure is called integrative hybrid power system. In general, there are two manners that can be adopted to carry out the power system integration in HEV. The first manner is engine-motor integration. For example, the engine and integrated starter/generator (ISG) can be integrated to form a light-duty HEV. The second manner is gear shift transmission system and electrical drive system integration. Some companies have already made some efforts in this research field. For example, the Insight HEV of Honda Company can be counted as the attempt at first integration manner. The AHS2 transmission of Allison Company and THS system of Toyota Company can be called the attempt at the second integration manner. This paper presents the idea of E.T.Driver and the project of E.T.Driver has already been launched. The E.T.Driver is to integrate the motor and transmission into a power unit assembly which can perform the drive, generate electricity, regenerative braking function and power transmission function. The E.T. Driver can be used in different sizes and different disposal structures of HEV if the E.T.Driver is designed into a series. The conventional vehicle will be rebuilt into a pure electric vehicle if the

E.T.Driver is adopted solely and no other power drive device is employed. Similarly, the E.T. Driver also can be used in other alternative energy sources vehicles, for example, the Fuel Cell Vehicle (FCV). So the extensive use of E.T.Driver will greatly promote the research and development of HEV and accelerate its industrialization because of the universal characteristic and adaptability of E.T.Driver. On the one hand, the E.T.Driver can control motor and transmission system concentratively, consequently helps to improve work efficiency of hybrid power system. On the other hand the E.T.Driver helps to improve the integrated level and reliability by reducing the component number of the whole vehicle, thus helping to enhance the maintenance and use of the vehicle. The match cycle and difficulty degree can be reduced; the research and production cycle also can be shortened because of less components number.

The motor usually couples with the transmission through the input shaft of transmission in most HEV. The velocity will be decreased because the friction clutch will be detached and the driving torque will be interrupted during the gear shift course. Furthermore, because the moment of inertia of motor is added to the input shaft of transmission, the added moment will delay the synchronization time between the flywheel and friction clutch. In reference literatures of AMT [1], most researches are focus on how to control the transmission driving torque transmitted by friction clutch and by adjusting the friction torque of clutch to reduce the slipping friction work and shock intensity. The control strategy [2] [3] [4] is a little complex correspondingly. The special structure of E.TDriver can greatly reduce the input driving torque of transmission during the gear shift course. Therefore, the slipping friction work of friction clutch and shock intensity of vehicle can be both reduced to a very small value or can be controlled to a satisfying degree. At the same time, the E.TDriver can maintain the velocity smooth during the gear shift course and increases the riding comfort.

2 The basic principle, structures and the characteristics of E.T.Driver

2.1 Principle

The E.T.Driver presented in this paper is to integrate motor with conventional transmission into an integrative unit assembly. The E.T.Driver is a new type of transmission power unit assembly which is highly integrative in mechanism-electricity-liquid. The mechanism includes the gear shift transmission unit, the main body of electric motor [5][6][7], the power coupling unit and the power-output part of hybrid power system. The electric system includes the control unit of the gear shift transmission system, power coupling control unit and the electromagnetism system, which translates the electrical energy into mechanical energy. The liquid system includes hydraulic actuator, cooling lubricating system of motor and transmission system.

2.2 The constitution of E.T.Driver

E.T.Driver may have many structures types. The design proposal is presented as follows:

(1) Motor with AMT is integrated into the E.T.Driver.

(2) Motor with epicyclic gear transmission is integrated into the E.T.Driver.

(3) Motor with continuously variable transmission (CVT) or motor with double clutch transmission is integrated into the E.T.Driver.

The development of the third type of E.T.Driver is based on (1) and (2).

3 The specific structure type of E.T.Driver based on the output shaft of AMT

There are two structure types E.T.Driver, which are based on AMT. The type depends on whether the motor is placed on the front or on the rear of AMT. The first type is to mount the motor on the input shaft of AMT and the rotor of motor is coupled with the input shaft of AMT directly or with a coupling device. The second type is to mount the motor on the output shaft of AMT and the rotor of motor is coupled with the output shaft of AMT directly or with a coupling device. The coupling device adopts the gear device, which can be an epicyclic gear or a pair of reducing gears. The function of the gear device is to reduce the output rotational speed and increase the output torque of motor at the same time. The motor also can couple its power directly to the input shaft or output shaft of AMT by fixing the rotor of motor directly onto the input shaft or output shaft of AMT. This paper mainly discusses the second type of E.T.Driver which is based on the output shaft of AMT. An epicyclic gear or a pair of common reducing gears can be adopted to help the motor output its power to the output shaft of AMT. The picture of E.T.Driver based on AMT output shaft is shown in Fig.1 and Fig.2.

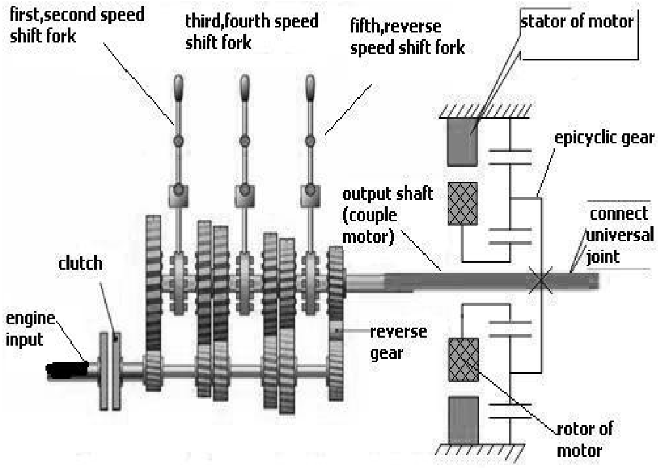


Fig.1 E.T.Driver for which the motor mounted on the output shaft of AMT, with its rotor coupling with the output shaft of AMT by epicyclic gear.

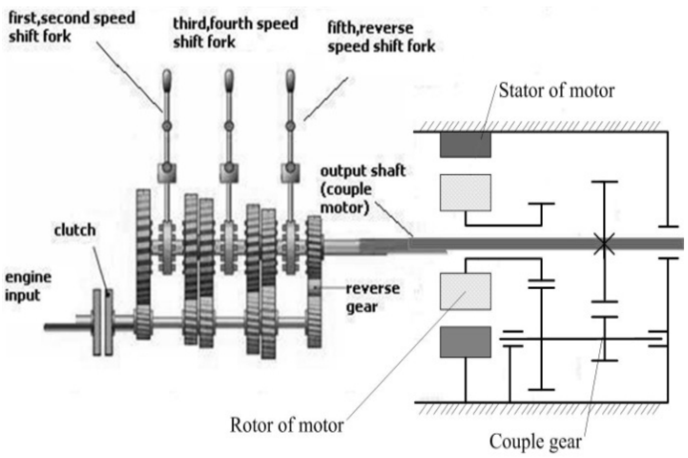
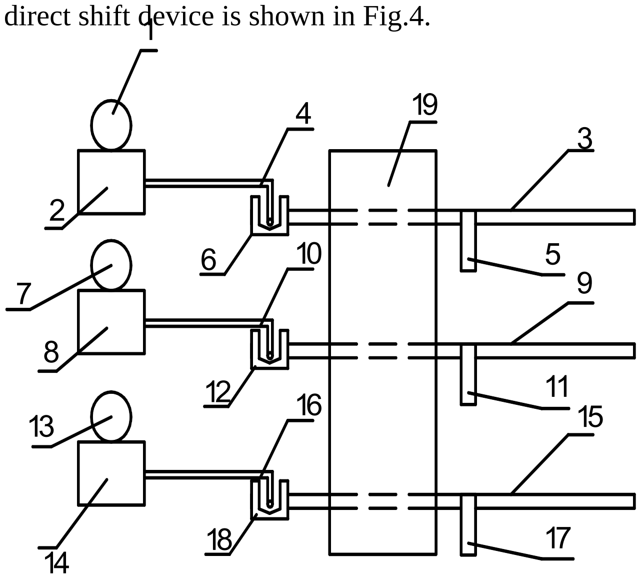


Fig.2 E.T.Driver for which the motor is mounted on the output shaft of AMT, with its rotor coupling with the output shaft of AMT by a pair of reducing gears

The conventional AMT shift mechanism and AMT clutch detachment/engagement device generally adopt conventional hydraulic drive device. The conventional gear shift courses of AMT also need three steps---quit gear, then select a new gear and finally engage the new gear. But in E.T.Driver which is based on AMT, the gear shift mechanism adopts the motor shift device to perform direct shift function. The motor shift mechanism can shift gear directly and the conventional select gear device and select gear course have been canceled. The gear shift course of motor direct shift device only include two steps——quit a gear and then engage a new gear. The gear shift time has been shortened and the quality of gear shift is improved consequently. The sketch of motor direct shift device in five speeds AMT is shown in Fig.3. The real motor direct shift device is shown in Fig.4.



1: gear shift motor of first/reverse speed 2: gear shift mechanism of first/reverse speed(switch rotation motion to linear motion) 3: fork-axles of first/reverse speed 4: work driving arm of first/reverse speed 5: first/reverse speed shift fork 6: first/reverse speed push groove 7: gear shift motor of second/third speed 8: gear shift mechanism of second/third speed(switch rotation motion to linear motion) 9: fork-axles of second/third speed 10: work driving arm of second/third speed 11: second/third speed shift fork 12: second/third speed push groove 13: gear shift motor of fourth/fifth speed 14: gear shift mechanism of fourth/fifth speed(switch rotation motion to linear motion) 15: fork-axles of fourth/fifth speed 16: work driving arm of fourth/fifth speed 17: fourth/fifth speed shift fork18: fourth/fifth speed push groove 19: fixed part

Fig. 3 The sketch of motor direct gearshift device in five speed AMT

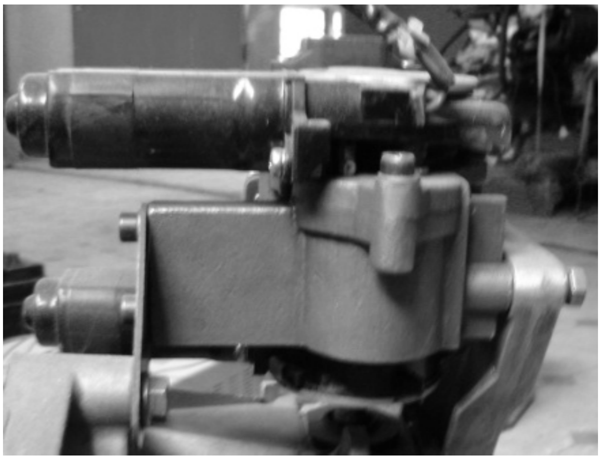


Fig. 4 real motor direct shift device

4 The simulation analysis of shift application of E.T.Driver during gear shift course in HEV

4.1 The function of E.T.Driver during HEV gearshift course

The E.T.Driver which is based on the output shaft of AMT can not only provide drive power independently and transmit the power from engine to wheel as a new type of highly integrative transmission drive unit assembly, but also can output driver power independently and maintain the drive power of HEV uninterrupted during the gear shift course. The E.T.Driver can keep the velocity increasing continuously or maintain the velocity without any decrease during the gear shift course. Consequently this can reduce the gear shift impact, avoid power interruption and enhance the riding comfort and driving smoothness. Although the detachment of clutch leading to the power of engine is interrupted, the motor of E.T.Driver can still provide the drive power, so the driving smoothness and gear shift quality can be greatly improved and the riding comfort can be enhanced at the same time.

4.2 The parameters of E.T.Driver and the main specification of hybrid electric bus to which the E.T.Driver can be applied in this research project.

1)Engine——the parameters of Commins ISBE170 are shown in Table 1, the relationship between torque, speed and acceleration pedal open is shown in Fig.5.

Table 1 Commins ISBE170 parameters

Engine model	Max. Power PS @ rpm	Peak Torque Nm @ rpm	Profile:				Displacement:	3.9 liters
ISB^e–170	167 @ 2500	600 @ 1200-1700	Length	Width	Height	Weight (dry)	Total lubrication system capacity:	39 liters
4 cyl.			810 mm	720 mm	820 mm	370 kg	Engine cooling system capacity	8.5 liters

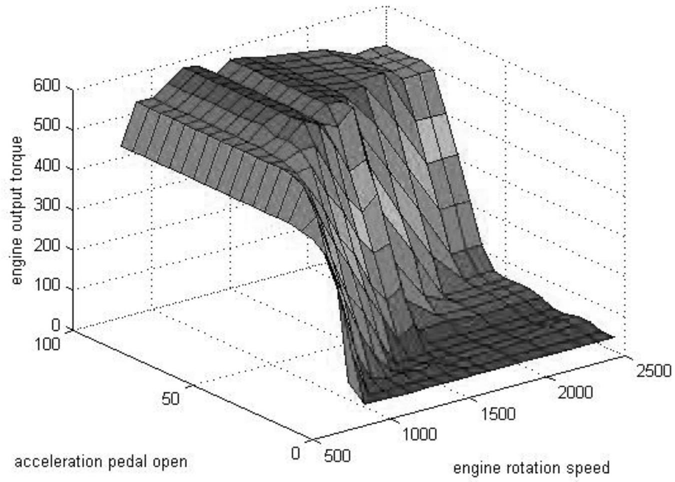


Fig.5 torque, speed and acceleration pedal open correlations

2) Permanent magnet--- synchronous reluctance motor and the corresponding motor control unit used in E.T.Driver

The E.T.Driver's motor parameters and characteristic are shown in Table 2, Fig.6 and Fig.7. Interior permanent magnet——synchronous reluctance motor and its motor control units are adopted. Interior permanent magnet —— synchronous reluctance motor has lots of advantages and is widely used in the drive power system of electric vehicles and hybrid electric

vehicles
.

Peak Torque	630Nm
Maximum Current	400A rms
Continuous Torque	90Nm
Continuous Power	45kW
Peak Efficiency	93%
Peak Electrical Power	125kW
At Voltage of	336VDC
Nominal Speed	2k rpm
Maximum Speed	6k rpm
Weight	188.6kg
Diameter	394mm
Length	520mm

Table 2 parameters of motor

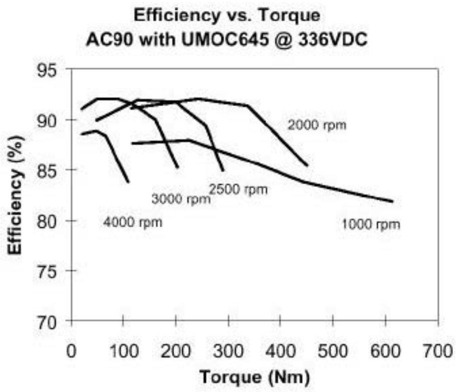


Fig. 6 motor torque efficiency

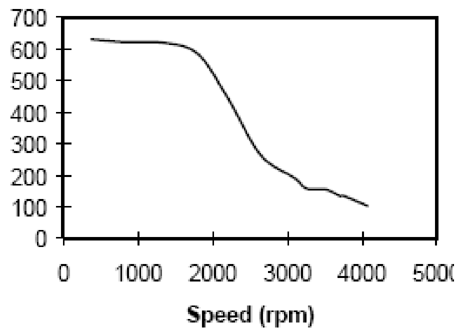


Fig. 7 relationship between speed and torque of motor

3) The ratio of speed of E.T.Driver is shown in Table 3

Table 3 Ratio of speed of E.T.Driver

Gear	ratio	number of input gear teeth	Number of output gear teeth
reverse	5.22	27	141
1st speed	6.11	18	110
2nd speed	3.389	59	200
3rd speed	2.05	20	41
4th speed	1.32	25	33
5th speed	1	10	10

4) The parameters of SWB6116HEV hybrid electric bus

The power layout of hybrid electric bus is shown in Fig.8. The E.T.Driver based on the output shaft of AMT is an 863 national project and is employed in the SWB6116HEV hybrid electric bus project. The SWB6116HEV hybrid electric bus is shown in Fig.9.

4.3 Establishment of the simulation model based the simulationx software

The simulation model was established, taking the case of gear shifting from first speed to third speed as an example. The Germany ITI company's simulationx software is adopted here to establish the simulation model.

The aim of this simulation model is to compare the differences between E.T.Driver and common AMT in HEV gear shift course. First of all, the gear shift velocity of AMT from first speed to third speed should be obtained. The velocity of SWB6116HEV hybrid electric bus from first speed to third speed is 17.5km/h during 0~50km/h acceleration course through several times of road test. The road test data are recorded by CANOE software, the recorded velocity data is shown in Fig.10.

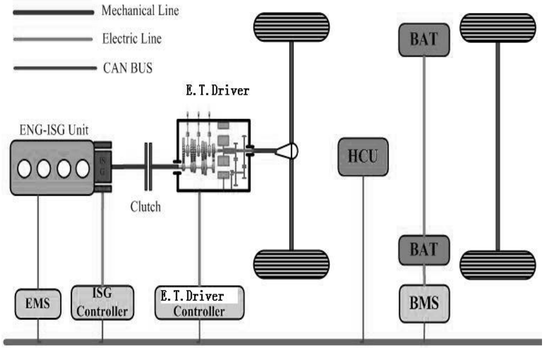


Fig.8 power layout of hybrid electric city bus

Fig.9 SWB6116HEV hybrid electric city bus

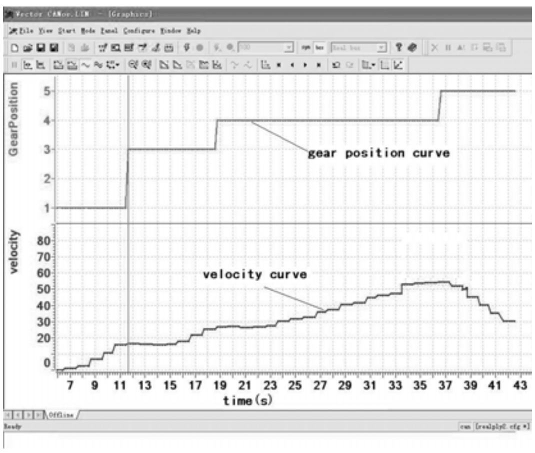


Fig.10：Gear position and velocity curve from first speed to third speed

4.3.1 Establishment of simulation model

1) Engine model

Firstly, every cylinder control model is established, and then the four cylinder control models are integrated to establish the whole engine model. The engine model outputs torque according to the universal performance characteristics map of engine strictly. The engine model is shown in Fig.11.

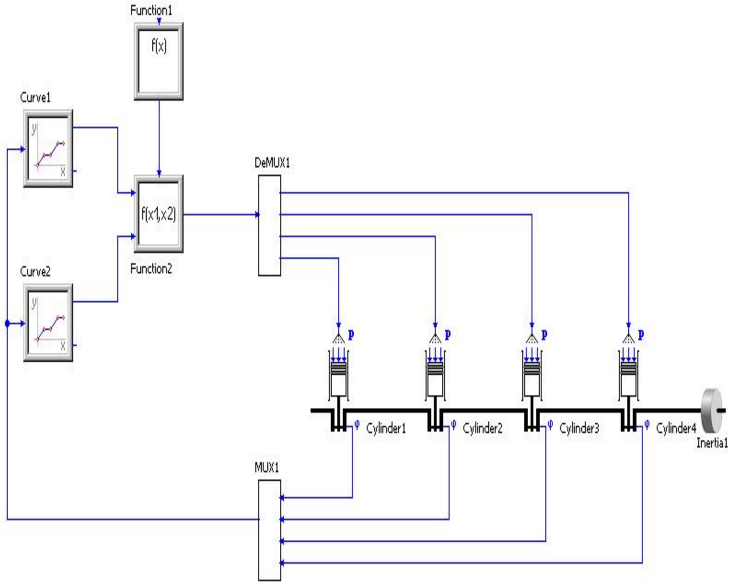


Fig.11 engine model

2) E.T.Driver model

The E.T.Driver model was established by combining the motor model and AMT model. Of course, some components models of E.T.Driver can be adopted which has already been built in the simulation software, for example, the clutch and motor component [8] [9] [10].

a) Clutch model

The type of clutch：JL420，the parameters of clutch are shown in Table 4：

Table 4 parameters of clutch

title	value
H (release lever adjust height)	75±0.4(mm)
Mcmax(Nm)(max. friction torque of clutch)	19656±1645
m1 (kg)(mass of pressure plate unit assembly)	44
m2 (kg) (mass of clutch disk unit assembly)	8.3
J (kg.m^2) (inertia of pressure plate unit assembly)	1.369
n (rpm)(max. enable rotational speed of clutch)	2700
P(N) (pressing force of pressure plate)	2090
F(N) (maximal detachment force)	4644
S(mm)(detachment distance)	10^2

The simulation software has the clutch model, so the clutch model can be used directly. The corresponding parameters of clutch just need to be input. The pressing force parameter of the clutch model can be calculated through equation (1):

$$T_c = Z\int_{R1}^{R2} \mu P 2\pi R^2 dR = \frac{2}{3}\pi Z \mu P (R_2^3 - R_1^2)$$

（1）

in equation（1）：

T_c——the transmission torque of clutch（Nm）;

Z——friction face number；

μ——friction coefficient;

P——pressing force of pressure plate(N)；

R1，R2——the inner and out radius of friction plate working face(m)

The value of transmitted torque by friction clutch can be controlled by controlling the value of the pressure force of clutch. The coordination control of engine and E.T.Driver can be coordinated according to the whole vehicle control strategy and gear shift strategy. The clutch model is shown in Fig.12. The clutch model parameters are shown in Fig.13。

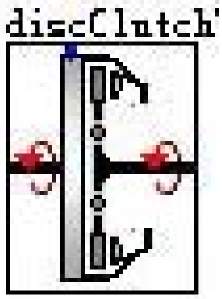


Fig.12 clutch model

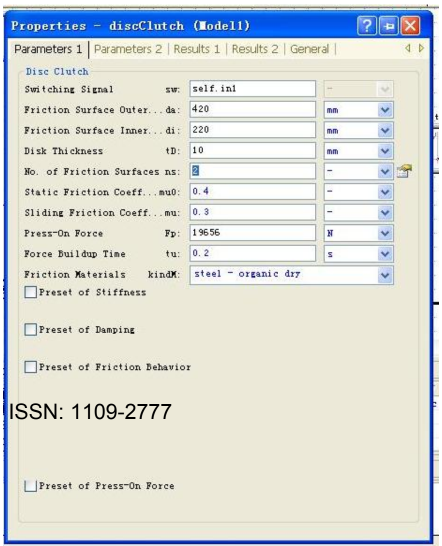


Fig.13 parameters of clutch model

b) Interior permanent magnet synchronous motor model

The simulation software has the interior permanent magnet synchronous motor model [11], so the motor model can be directly adopted. The sketch of the motor control model is shown in Fig.14.

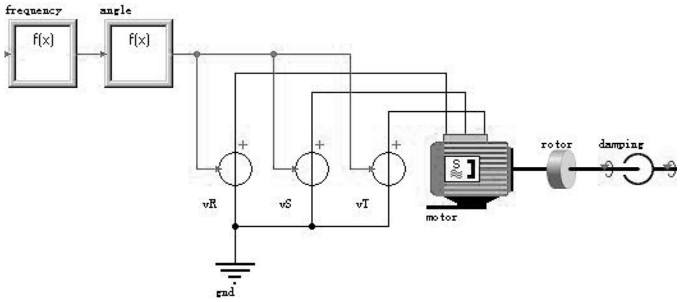


Fig.14 motor control model sketch

The transmission part model of E.T.Driver is shown in Fig.15.

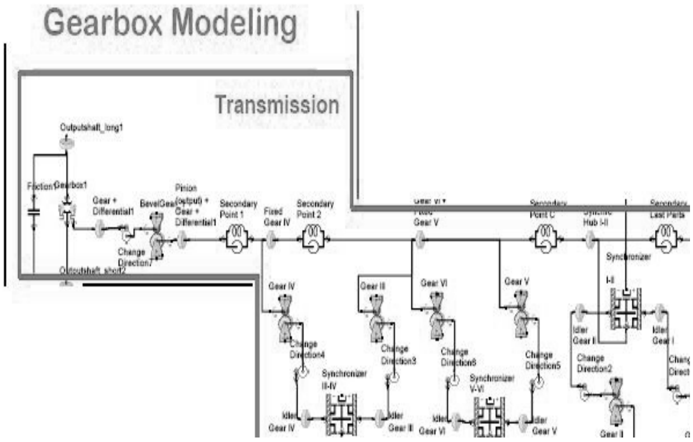


Fig.15 transmission part model of E.T.Driver

3) Air drag, acceleration resistance and rolling resistance model

These resistance values can be calculated through equation （2）, （3） and （4）. The vehicle running resistance under any running velocity situation can be obtained through setting the corresponding equation in the resistance model in the simulation software.

$$F_W = \frac{C_D A u_a^2}{21.15} \qquad (2)$$

In equation （2）:

F_W——air drag（N）；

C_D——air drag coefficient；

A——front face area(m^2)；

u_a——vehicle velocity(km/h)。

$$F_f = Gf\cos\alpha \qquad (3)$$

In equation（3）:

F_f——rolling resistance(N)；

G——gravity of vehicle

f——coefficient of rolling resistance

α——slope angel(°)

$$F_j = \delta m \frac{du}{dt} \qquad (4)$$

In equation (4):

F_j——acceleration resistance(N)；

δ——vehicle rotation mass conversion factor；

m——vehicle mass（kg）；

$\frac{du}{dt}$——acceleration（m/s^2）。

The simulation model of whole vehicle is shown in Fig.16.

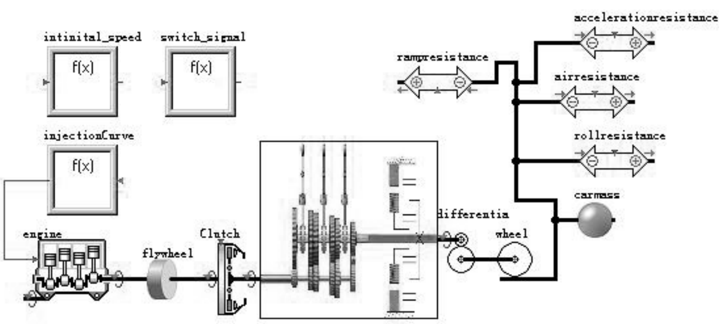


Fig.16 simulation model of whole vehicle

4.4 The application of E.T.Driver during gear shift course

The E.T.Driver has the transmission function, the electricity generation function and the power drive function, so the whole vehicle control strategy and gear shift strategy must consider the power coordination between engine and E.T.Driver. In the hybrid electric vehicle gear shift control course, the working conditions for the E.T.Driver can be divided into two situations in spite of economical gear shift strategy or dynamic gear shift strategy. The whole vehicle energy management strategy and the state of charge (SOC) of battery are also taken into consideration to obtain the two working situations of E.T.Driver at the same time. The two situations of E.T.Driver during gear shift course are described below [12]:

A. The E.T.Driver has the ability to provide the total driving request torque of HEV. Under this situation, the electric motor of E.T.Driver works in positive rotation as an electromotor to provide its total driving torque for the HEV or the electric motor of E.T.Driver works in reverse rotation as an electric generator to generate electricity in regenerative braking running working situation.

B. The whole HEV driving requests torque beyond the ability that the motor of E.T.Driver can provide. (Positive driving torque or reverse generate electricity resistance torque).

In situation A, the E.T.Driver can provide the HEV driving request torque independently. Therefore the E.T.Driver can maintain the velocity of HEV stable or can keep the velocity continuing to increase during gear shift course under the condition of shifting from low speed to high speed. The flywheel rotational speed will track the clutch rotational speed after the aim gear engaged .When the rotational speed difference between flywheel and clutch disk is small enough, the flywheel and clutch disk can engage as quickly as they can. The course in which the flywheel rotational speed tracks the rotational speed of clutch disk can last a little longer time because the driving request torque of HEV still can be provided by E.T.Driver during the gear shift course. There is very little abrasion and impact of clutch in the situation A, because on the one hand the rotational speed difference between flywheel and clutch disk is very small when they engages ,on the other hand there is very small friction torque is transmitted by clutch. Situation A is universal in city traffic jamming situation and occupy above 70% of the overall HEV running working condition. The vehicle continually shifts in traffic congestion situation and the engine runs in noneconomic work zone in most of the time. The E.T.Driver can show its advantage in this situation. It can not only help to enhance the shift quality and riding comfort, but also can drive HEV in pure electric driving mode when the HEV runs in start phases or in low speed phases. The city bus continually shift because the city bus run line has an outstanding characteristic--- the city bus runs in low velocity in most of the time. The E.T.Driver is suitable for this work situation. The real working situation for two city bus run lines are shown in Fig.17 and Fig.18.

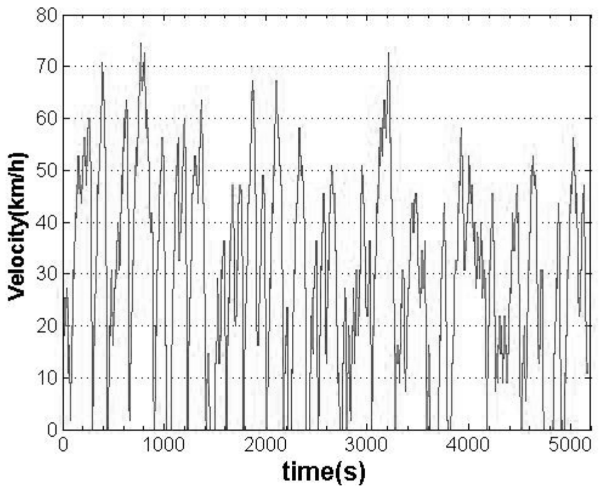


Fig.17 velocity change curve of city bus line 1

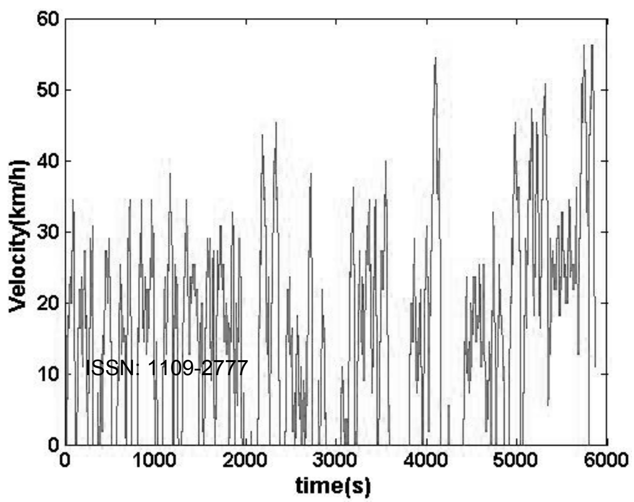


Fig.18 velocity change curve of city bus line 2

In situation B, the E.T.Driver provides the maximal driving torque which it can provide according to the gear shift strategy during the gear shift course. Because the driving torque provided by E.T.Driver can’t meet the whole driving request torque, the other driving torque needs to be provided by engine, so the clutch needs to engage quickly to transmit the driving torque that provided by engine. The flywheel possibly has not enough time to reach the same rotational speed of clutch disk, so the rotational speed difference between flywheel and clutch disk will becomes a little greater. In this situation, in order to control the shock intensity and speed up the engagement speed between clutch disk and flywheel, the output torque of E.T.Driver can be adjust to reduce the value of $\frac{i_0 i_g \eta_T}{\delta m r}\frac{d(T_c + T_m / i_g)}{dt}$, which described in equation (8).In other words, if the friction torque T_c transmitted by clutch increases too rapid, the output torque of E.T.Driver T_m can be adjusted to reduce quickly at the same time, so the value of

$\frac{i_0 i_g \eta_T}{\delta m r}\frac{d(T_c + T_m / i_g)}{dt}$ can be controlled under a satisfied level. The E.T.Driver also even can output reverse electric power generation resistance torque to reduce the value of $\frac{i_0 i_g \eta_T}{\delta m r}\frac{d(T_c + T_m / i_g)}{dt}$ to control the shock intensity during the clutch engagement course.

Accordingly, the gear shift quality and run smoothness also can be controlled to a satisfied level in situation B.

After the gear shift is accomplished, the output torque of E.T.Driver and engine should be added or be reduced over again according to the HEV control strategy and energy management strategy both in Situation A and B.

This simulation model takes first speed to third speed as an example. The initial gear position is set to first speed in advance. The HEV begins to shift when the velocity reaches the shift velocity of 17.5km/h. The E.T.Driver begins to output driving torque instead of engine when the clutch begins to detach. The output driving torque value of E.T.Driver can be calculated through equation (5).

$$\frac{T_m i_0 \eta_T}{r} = Gf\cos\alpha + Gi + \frac{C_D A u_a^2}{21.15} \qquad (5)$$

In equation（5）:

T_m——output torque of E.T.Driver（N.m）;

i_0——ratio of final drive

i——degree of slope

η_T——efficiency of transmission；

r——wheel rolling radius (m);

the other parameters can be seen the illustrations of equation（2）,（3）and（4）.

5 The simulation result analysis

5.1 gear shift course of HEV equipped with traditional AMT

The hybrid electric bus velocity changes curve is shown in Fig. 19 during the gear shift course from first speed to third speed of HEV equipped traditional AMT. The acceleration changes curve is shown in Fig. 20.The clutch changes curve is shown in Fig. 21. The gear shift time is set to one second based on actual measure of gear shift time of hybrid electric bus and some references are considered at the same time.

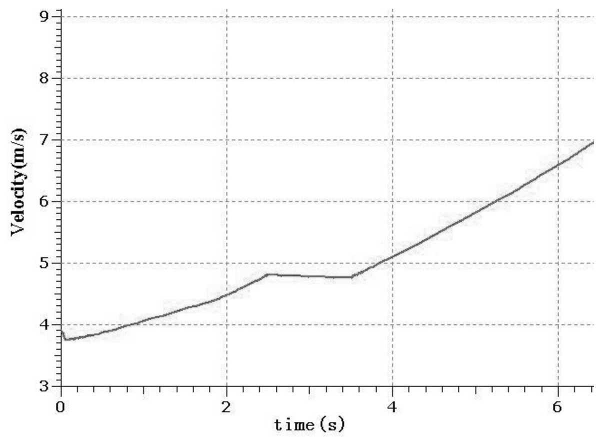


Fig. 19 the velocity changes curve（the AMT begins to shift when the velocity reaches 17.5km/h at 2.5 second and finishes shifting at 3.5 second）

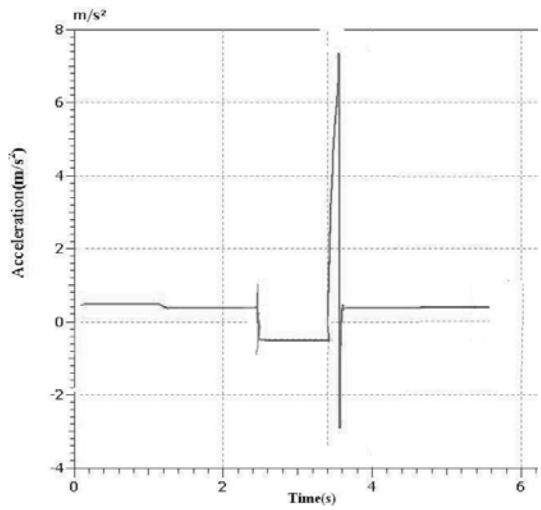


Fig.20 acceleration changes curve

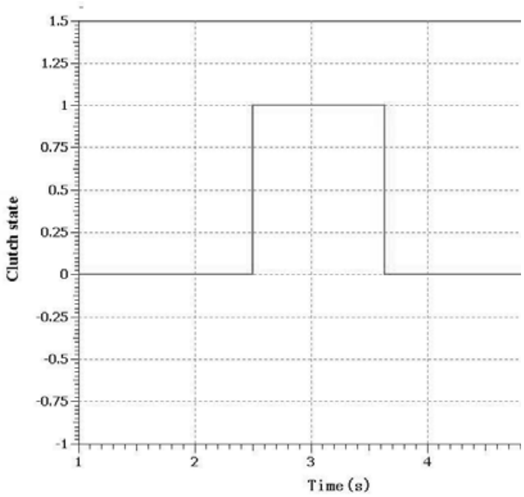


Fig. 21 engagement and detachment situation curve of clutch (0——engagement，1——detachment)

From Fig. 19 it is found the velocity begins to drop when the AMT begins to shift until the clutch disk resumes engaging. From Fig. 20 it is found the acceleration drops to negative value after the clutch disk detaches and there is oscillation of acceleration occurs when the clutch detaches and engages.

5.2 gear shift course of HEV equipped with E.T.Driver

The velocity changes curve in the situation of E.T.Driver providing driving torque is shown in Fig. 22 and Fig. 23. Acceleration changes curve in the situation of E.T.Driver providing driving torque is shown in Fig. 24. The flywheel and clutch disk engagement process during gear shift course is shown in Fig. 25.

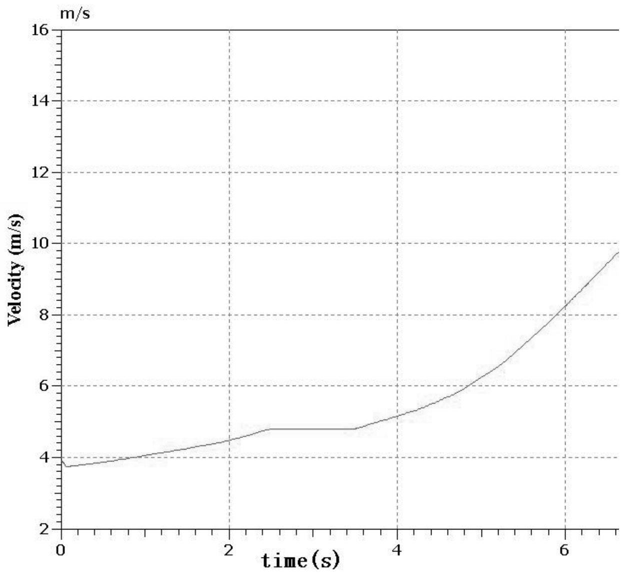


Fig. 22 the velocity is maintained without any change during the gear shift course (the E.T.Driver output torque just can keep the velocity stable)

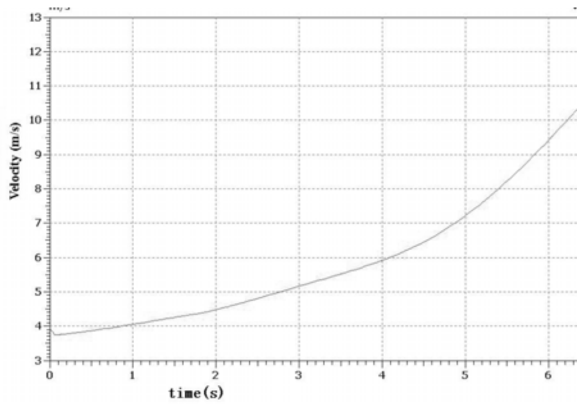


Fig. 23 the velocity continues to increase during the gear shift course (the SOC of battery is high enough, so the output torque of E.T.Driver can keep the velocity increasing during the gear shift course)

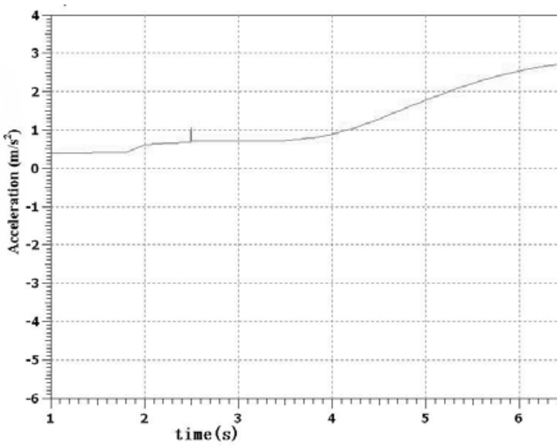


Fig. 24 acceleration changes curve

From Fig. 24 it is found that the acceleration remains stable during the gear shift course, especially there is no oscillation occurs in the engagement moment.

From Fig. 22 it is found that the HEV velocity is maintained stable during the gear shift course in the situation of battery SOC is a little low, the output torque of E.T.Driver can only keep the HEV velocity from dropping. From Fig. 23 it can be found the HEV velocity continually increases during the gear shift course because the battery SOC is high enough to support the motor of E.T.Driver outputs enough high torque to keep the HEV velocity increasing during gear shift course.

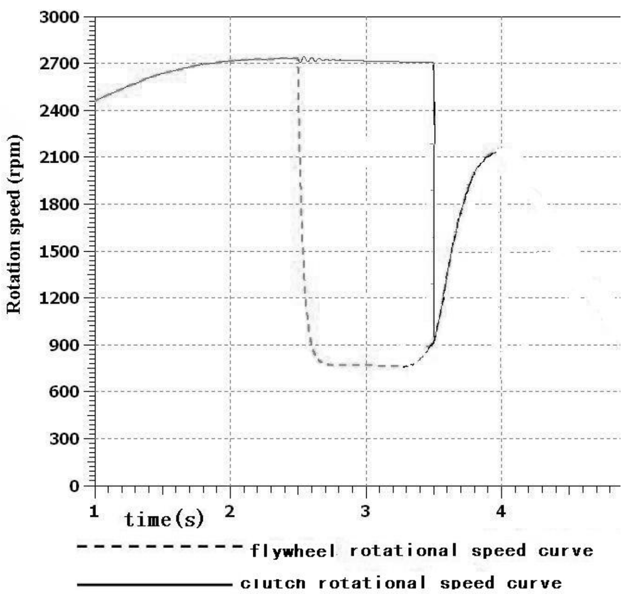


Fig. 25 flywheel and clutch disk engagement process curve in gear shift course.

In Fig. 25 it is found that the clutch disk detaches from the flywheel at the beginning of shift, and then the flywheel rotational speed falls to the idle speed (750 rpm) from the rotational speed of engine in first speed. After that, the flywheel rotational speed will track the clutch disk rotational speed. The clutch disk rotational speed falls to about 913rpm after the new gear is engaged. The new gear position is third speed in this model. The rotational speed 913rpm is calculated through equation (6).

$$u_a = 0.377 \frac{rn}{i_g i_0} \quad (6)$$

In equation (6):

u_a ——vehicle velocity(km/h)

n— clutch rotational speed(rpm)

r—— wheel rolling radius(m)

i_g ——ratio of E.T.Driver

i_0 ——ratio of final drive

The velocity when the gear shifts from first speed to third speed is 17.5km/h; the wheel rolling radius is 0.508m; the ratio of third speed is 2.05; the ratio of final drive is 4.875. Therefore it can be calculated that the clutch rotational speed is about 913rpm after the third speed is engaged. The flywheel rotational speed is controlled to track the clutch disk rotational speed. Because the clutch disk rotational speed can be forecasted by equation (6) in different gear positions, the target rotational speed for flywheel which the flywheel should reach can also be set in advance and the ISG also can help the engine to adjust its rotational speed. The flywheel and clutch disk will engage as quickly as they can when the rotational speed difference between the flywheel and the clutch disk is small enough. The perfect situation is when the flywheel and clutch disk reach 913rpm simultaneously, so the rotational speed difference between the flywheel and the clutch disk is equal to zero in theory. Flywheel and clutch disk will increase their rotational speed together after the engagement is completed.

5.3 The function analysis of E.T.Driver improving the shift quality during gear shift course

A conclusion can be drawn from the simulation above. The E.T.Driver based on the output shaft of AMT can greatly reduce the jerk and improve run smoothness and riding comfort during the HEV gear shift course. The clutch disk and the flywheel engage quickly when the rotational speed difference between the flywheel and the clutch disk is small enough. How the E.T.Driver improves the shift quality during the gear shift course will be elaborated in details based on the jerk and slipping friction work calculation equation s as below.

5.3.1 Jerk intensity

The jerk mainly happens in the flywheel and clutch disk engagement course. The jerk calculation equation is shown in equation (7).

$$J = \frac{d^2u}{dt^2} \qquad (7)$$

The jerk calculation equation also can be converted to equation (8) in real gear shift course.

$$J = \frac{d^2u}{dt^2} = \frac{i_0 i_g \eta_T}{\delta mr}\frac{d(T_c + T_m / i_g)}{dt} \qquad (8)$$

In equation（8）：

J——jerk(m/s^3)；

T_c——the real torque transmitted by clutch（Nm）。

From equation (8) it is found that the jerk intensity value is determined mainly by $\frac{d(T_c + T_m / i_g)}{dt}$, which is the derivative of the sum of torque transmitted by clutch and the output torque of E.T.Driver.

In gear shift situation A in which the output torque of E.T.Driver can provide enough driving torque to maintain the vehicle velocity stable or keep the velocity continuing to increase, the flywheel has enough time to synchronize the rotational speed of clutch disk and the drive power of HEV won't be interrupted. When the rotational speed difference between flywheel and clutch disk is small enough, the flywheel and the clutch disk will engage as quickly as they can. Under this situation, since the rotational speed difference between the flywheel and clutch disk is very small, the jerk intensity also is very small during the engagement course of flywheel and clutch disk.

In gear shift Situation B, because the driving request torques value of the whole vehicle beyond the ability that E.T.Driver can provide, the clutch needs to engage quickly to transmit the driving torque that provided by engine. In order to control the shock intensity and speed up the engagement speed between clutch disk and flywheel at the same time, the output torque of E.T.Driver can be adjust to reduce the value of $\frac{i_0 i_g \eta_T}{\delta mr}\frac{d(T_c + T_m / i_g)}{dt}$, so the jerk intensity also can be control to a very little value according to equation (8).

Reducing the jerk of the clutch disk is a relatively complex course. The engine control, clutch disk control and their cooperation all need to be well thought out, so the details of how E.T.Driver cooperates with the engine to reduce the jerk concretely will be discussed in the further work.

5.3.2 Slipping friction work

The main factor that affects the life span of the clutch is the slipping friction work during the gear shift course. The slipping friction work mainly happens in the flywheel and the clutch disk engagement course, the slipping friction work in the engagement course is defined as below:

$$W = \int_{t_0}^{t_c} T_c(t)\left|\omega_e(t) - \omega_c(t)\right| dt \qquad (9)$$

In equation (9):

W——slipping friction work (J)(it reflects how much mechanical energy is transferred to thermal energy and abrasion during the engagement course of clutch.)

ω_e——rotational speed of engine；

ω_c——rotational speed of clutch disk；

t。——the time when the clutch begins to engage and transmit torque；

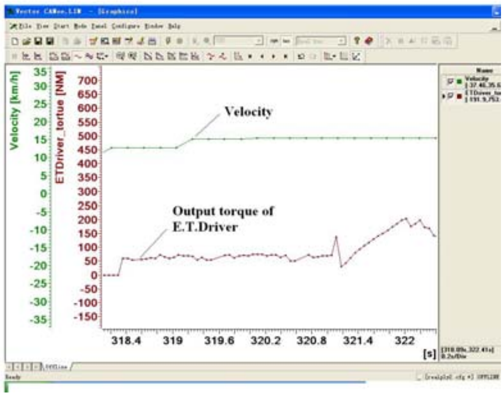
t_c——synchronization time when the clutch disk begins to synchronize with the flywheel；

From equation (9) it is found that the slipping friction work is in direct proportion to the friction torque, time and rotational speed different between flywheel and friction clutch. The friction torque is bigger, the engagement time is longer and the difference between the flywheel and the clutch disk is bigger, the slipping friction work is bigger and the temperature is higher, the life span of the clutch is shorter. The slipping friction work and the jerk intensity are opposite to each other. Pursing less slipping friction work will lead to greater jerk in real gear shift course. Similarly, to reduce the jerk, the slip time between the flywheel and the clutch disk will become longer; the slipping friction work will increase. The E.T.Driver based on the output shaft of AMT solved this problem perfectly. The E.T.Driver can provide the driving request torque in gear shift Situation A, so the flywheel has enough time to track the rotation speed of clutch disk. The rotation speed difference between the flywheel and clutch disk is very little, so they can engage quickly and do not need too much time to synchronize with each other. Therefore, the slipping friction work is also very little according to equation (9).

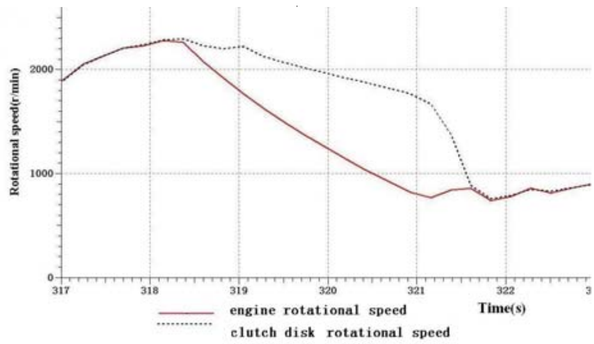
In gear shift situation B, because the value of whole vehicle driving request torque beyond the ability that the E.T.Driver can provide, the clutch needs to be engaged quickly to transmit the driving torque of engine. The flywheel has not enough time to reach the same rotational speed of the clutch disk. Therefore, the rotational speed difference between the flywheel and the clutch disk will be produced .Under this condition, the slipping friction work can't be avoided. However, as the E.T.Driver can provide a part of the driving torque, the friction torque T_c transmitted by the clutch of E.T.Driver is still smaller than the friction torque transmitted by traditional AMT component. Furthermore, because of the adjustment function of E.T.Driver, the flywheel and clutch disk can engagement quickly and the jerk intensity also can be controlled to a very low level at the same time, so the engagement time is very short. So the slipping friction work of HEV equipped with E.T.Driver is also smaller than the slipping friction work of HEV equipped with traditional AMT according to equation (9).

6 Experimental validations

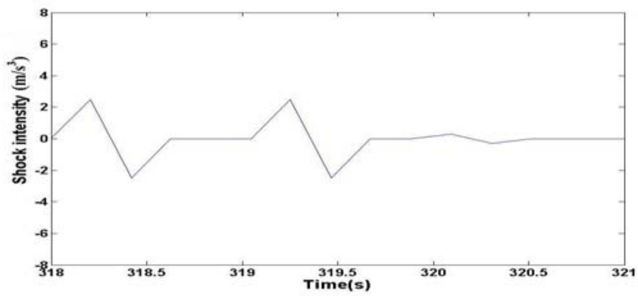
The experiment results of first gear to third gear shift course are shown in Fig.26. The road experiment has been carried out according to GB/T 19754-2005 《Test methods for energy consumption of heavy-duty hybrid electric vehicles》.



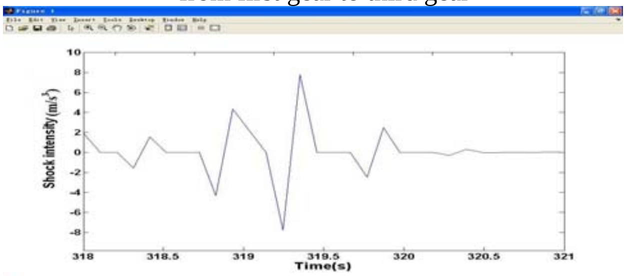
(a) The output torque of E.T.Driver and velocity change situation during the engagement course from first gear to third gear



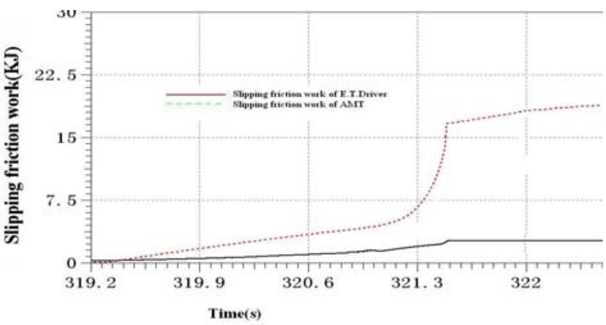
(b) Synchrodrive response of the clutch plate from first gear to third gear course



(c) Shock intensity change situation of E.T.Driver from first gear to third gear



(d) Shock intensity changes situation of AMT from first gear to third gear



(e) Contrast of slipping friction work between E.T.Driver and AMT from first gear to third gear course

Fig.26 the shift course from first gear to third gear and gear shift quality situation

From the Fig.26, it can be found that the driving torque of HEV do not be interrupted because the E.T.Driver can provide driving torque during the clutch separate course. The velocity can be kept steady or be kept continually increasing during the gear shift course. The shock intensity and slipping friction work of HEV equipped with E.T.Driver are obviously much better than the vehicle equipped with AMT. The driving smoothness of the HEV equipped with E.T.Driver is also enhanced greatly compared to the HEV equipped with AMT [13].

7 Conclusions

The HEV compositive power system is the kernel technology of HEV and is also a new and important research field today and in the future.

The special constitution of E.T.Driver based on output shaft of AMT is fully discussed. It is found the driving smoothness, riding comfort and the gear shift quality of HEV equipped with E.T.Driver can be greatly improved compared to traditional AMT during the gear shift course from the simulation results and road experiment. A new idea on HEV hybrid power system research is brought forth. The development of HEV key technologies will be made available by E.T.Driver. The next main research work is to perfect the control strategy and constitution of E.T.Driver based on the output shaft of AMT. More road experiments of HEV equipped with E.T.Driver will be carried out in order to better adjust and match the correlative control parameters among BMS (battery management system), VCU (vehicle control unit), EMU (engine management unit) and E.T.Driver controller. Other types of E.T.Driver, which based on epicyclic gear transmission, continuously variable transmission (CVT) or double clutch transmission, are also in the process of research and manufacture.

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