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Research on Analysis Method and Principle of Dual-Mode Electro-mechanical Variable Transmission Program

LI Hongcai, YAN Qingdong, XIANG Changle, and WANG Weida

National Key Lab of Vehicular Transmission, Beijing Institute of Technology, Beijing 100081 China

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Abstract: Automotive industry, as an important pillar of the national economy, has been rapidly developing in recent years. But proplems such as energy comsumption and environmental pullution are posed at the same time. Electro-mechanical variable transmission system is considered one of avilable workarounds. It is brought forward a kind of design methods of dual-mode electro-mechanical variable transmission system rotational speed characteristics and dual-mode drive diagrams. With the motor operating behavior of running in four quadrants and the speed characteristics of the simple internal and external meshing single planetary gear train, four kinds of dual-mode electro-mechanical transmission system scheme are designed. And the velocity, torque and power characteristics of one of the programs are analyzed. The magnitude of the electric split-flow power is an important factor which influences the system performance, so in the parameters matching design, it needs to reduce the power needs under the first mode of the motor. The motor, output rotational speed range and the position of the mode switching point have relationships with the characteristics design of the planetary gear set. The analysis method is to provide a reference for hybrid vehicles' design. As the involved rotational speed and torque relationships are the natural contact of every part of transmission system, a theory basis of system program and performance analysis was provided.

Key words: electro-mechanical variable transmission, dual-mode, rotational speed characteristics

1 Introduction

Automobiles, as the main means of transport and the important pillar industry of the national economy has been rapidly developing in recent years, but it also brings energy consumption, environmental pollution and many other issues[1-3]. Therefore, electric driving and electro-mechanical transmission which possess higher transmission efficiency and lower environmental pollution are the immediate focus of the study.

The dual-mode electrical and mechanical composite transmission is connected with multiple motors drive (usually 2) through planets and other components; in the engine input basically unchanged, alternating changes in the motor working status through the switching planetary components, make the transmission output speed continuously vary to meet the vehicle needs [4]. The dual mode hybrid transmission system of General Motors can insure the engine will run at a constant speed, and fuel efficiency can be increased by 25%[5].

In the field of hybrid power study, "mode" often represents the working state of hybrid power vehicles, such as: pure electric drive mode, hybrid driving mode, regenerative braking mode ... And the concept of the "mode" in this paper is the same with that of General Motors. It specially refers to changes with the rotational speed change trend of the motor.

This paper introduces the dual-mode electro-mechanical compound of the variable transmission principle, using the work characteristics of four quadrants of the motor and the functions of speed division and torque convergence of the planetary row, and presenting the scheme design method of the dual-mode electro-mechanical compound of variable transmission; and the rotate speed, torque and power characteristics of the scheme were analyzed; finally, the effect of the planetary row parameters on the rotational speed characteristics of the scheme were analyzed.

2 Principle of the dual-mode electro-mechanical variable transmission system

Motors are featured with the operate behavior of the four-quadrant motor, as shown in Fig. 1. In the first and the third quadrant the motor is in output power condition. In the second and the fourth quadrant the motor is in power generation and absorption condition.

When one of the two motors connects with the planet carrier, the other one connects with the sun gear or the ring gear, and the left link connects with power input. The

* Corresponding author. E-mail: armwtank@bit.edu.cn

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relationship of the speed of motor *A* is directly proportional to motor *B* while keeping the input rotational speed n_i stable in the first stage, as shown in Fig. 2. The rotational speed of motor *A*, n_A , pushes up alongside the *ad* line. The rotational speed of motor *B*, n_B , pushes up alongside the *fb* line. When output link connects with motor *B* in proportion, the output rotational speed n_o varies along the of line. When n_A is up to 0, system enters upon the second stage: n_A continues to rise alongside the *ade* line, and n_B varies along the *fbc* line. It can cause the rotational speed n_o to continue to rise alongside the *fe* line. If the rotational speed of motor *B* too high, it might change the mechanical connection form of the motor and the transmission system, and it can cause n_B to vary along the *fbe* line. At this stage, change in the relationship of output and motor *A* in direct proportion enable the output rotational speed n_o to sustained alongside the *fe* line.

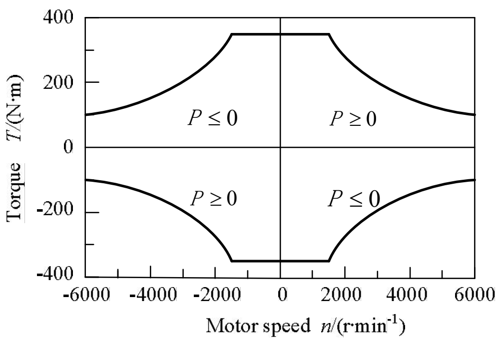


Fig. 1. Operate behavior of four-quadrant motor

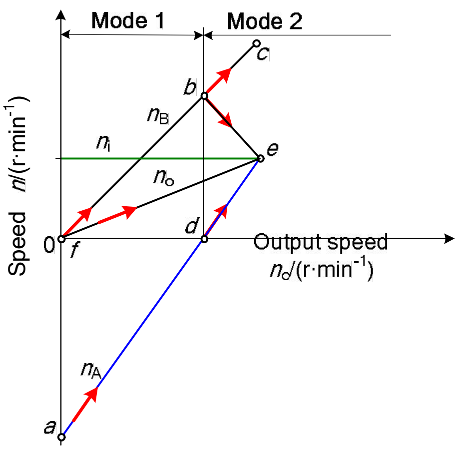


Fig. 2. Scheme of the principle of dual-mode electro-mechanical variable transmission system

3 Target design of dual-mode electro-mechanical variable transmission system

Design of the operate behavior of the electro-mechanical variable transmission system, is shown in Fig. 3[6-16]. In the first mode, motor *A* generates electricity, and motor *B* works by electricity; in the second mode, motor *B* generates electricity, and motor *A* works by electricity.

The program contains the following features:

(1) At least four basic components: input *i*, output *o*, motor *A* and motor *B*.

(2) Output *o* do not directly link to any items of input *i*, motor *A* and motor *B*.

(3) Output *o* is not directly connected to the input planetary row.

(4) In the first model, motor *B* as the role of electromotor was proportional to the output speed *o*;

(5) The rotational speeds of motor A and motor B change in the same direction in mode 1, and it is reverse in mode 2.

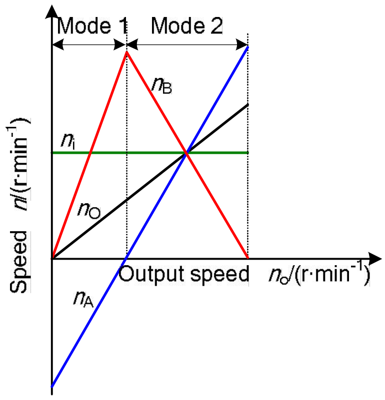


Fig. 3. Speed characteristic diagram of goal of dual-mode electro-mechanical variable transmission system

If we are given the design goal speed program, the planetary gear set rotational speed characteristics can be used to reversely solve the electro-mechanical variable transmission system structure.

4 Design of the dual-mode transmission strategy of the dual-star planetary gear set

The basic planetary gear set is composed of three basic components: the planet carrier, ring gear, and the sun gear. The internal and external meshing single-star planetary gear set has the following speed relationship[14]:

$$n_t + kn_q = (1+k)n_j \tag{1}$$

where n_t is the sun gear speed, n_q is the ring gear speed, n_j is the planet carrier speed, and k is the characteristics parameters.

For the dual-mode switching from the first mode to the second mode, it needs to control the control parts: the brake and the clutch; on the basis of the working status of which the brake parts have been switched before and after. The possible programs can be divided into two categories: the brake parts in the two models are involved in the work and in the program there are two planetary gear sets; the brake parts of the first mode does not participate in the work in the second mode, the row of which in the second mode is in a free state, three planetary gear sets exist in the program.

Double planetary gear sets program is only analyzed in this paper.

4.1 Form of input planetary gear set and output planetary gear set of human upper-limb

(1) In the first mode, the relationship of rotational speed of motor *A* is directly proportional to motor *B*, and the initial conditions are as follows: $n_B = 0; n_A < 0$. As a result, motor *B* can only be the planet carrier, and input *i* and motor *A* are the sun gear or the ring gear.

(2) In the second mode, the relationship of rotational speed of motor A is inversely proportional to motor *B*, $n_B > 0; n_A > 0$, and motor *B* can't directly connect with the first planetary gear set; In the two modes the relationship of rotational speed of motor *A* and the output speed are identical. The output end should connect with the first planetary row.

(3) In the first mode motor *B* acts as an electric motor, rotational speed of motor *B* is satisfied with the condition: $n_B > 0$. So, motor *B* acts as the sun gear or the ring gear of the second planetary row, and the planet carrier acts as the output end.

Combining with the specialty of the output characteristics, the possible forms of the first and second planetary row of the dual-mode composite planet is shown as Fig. 4 and Fig. 5.

(a) (b)

Fig. 4. Possible input form

(a) (b)

Fig. 5. Possible output form

4.2 Transmission strategy

With two kinds of input forms and two kinds of output forms, there can be $C_2^1 C_2^1 = 4$ kinds of transmission strategies.

The input form and output form, for example, can be used for analyzing the relationship of the connection and the rotational speed of the strategy. Motor *B* can't connect with the planet carrier of the first planetary row directly. The output end should connect with the planet carrier of the first and second planetary set. The connection of motor *A* and the basic components of the two planetary sets is achieved by the clutch. Thus, the first mode and second mode transmission diagrams are gained respectively. Finally, the dual-mode electro-mechanical variable transmission system diagrams are obtained, as shown in Fig. 6. All of four kinds of diagrams have been shown in Fig. 7.

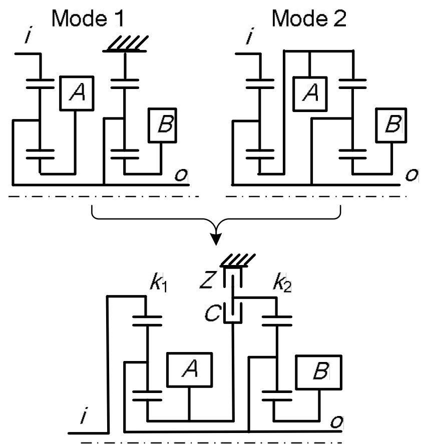
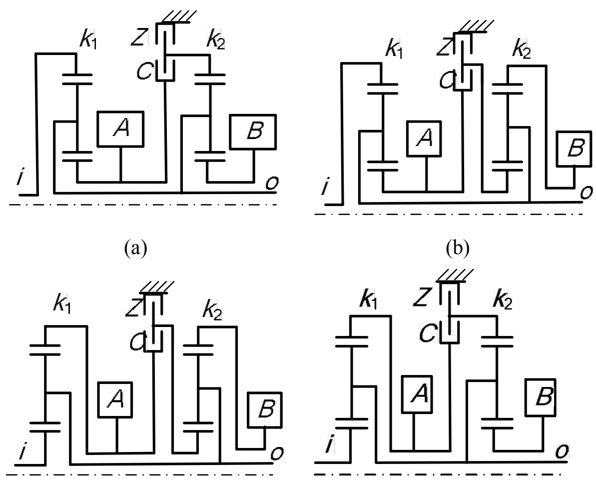


Fig. 6. Gaining process of the dual-mode electro-mechanical variable transmission system diagrams



(a) (b) (c) (d)

Fig. 7. Dual-mode electro-mechanical variable transmission system diagrams

5 The analysis of the rotational speed and torque characteristics of the program

In the paper only take the program (a), for example, to make the rotational speed and torque analysis. Table 1 is the operational status and the motor status of their control parts.

Table 1. Two operational status of control parts

Mode	*Z*	*C*	*A*	*B*
1	●	○	Generation	Electromotion
2	○	●	Electromotion	Generation

Note: ○ shows separation; ● shows engagement.

Under the first transmission mode brake *Z* is engaged and clutch *C* is separated, combining Eq. (1), the rotational speed satisfies the following relationship:

$$\begin{cases} n_A + k_1 n_i = (1+k_1)n_o \\ n_B = (1+k_2)n_o \end{cases} \tag{2}$$

Taking the input speed and output speed as independent variables, and the rotational speed of motor A and B as dependent variables, the rotational speed relationship between motor A and B can be abtained:

$$\begin{pmatrix} n_A \\ n_B \end{pmatrix} = \begin{pmatrix} -k_1 & 1+k_1 \\ 0 & 1+k_2 \end{pmatrix} \begin{pmatrix} n_i \\ n_o \end{pmatrix} \tag{3}$$

When transmission machine is uniform in rotation and omitting friction, the simple internal and external meshing single-star planetary gear set has the following torque relationship:

$$T_i : T_q : T_j = 1 : k : -(1+k) \tag{4}$$

where T_t is sun gear torque, T_q is the ring gear torque, T_j is the planet carrier torque.

Under the first mode, made the mechanical equilibrium analysis on the components where the motors are found:

$$\begin{cases} T_A = \dfrac{1}{k_1} T_i \\ T_B + \dfrac{1+k_1}{(1+k_2)k_1} T_i = \dfrac{1}{1+k_2} T_o \end{cases} \tag{5}$$

$$\begin{pmatrix} T_A \\ T_B \end{pmatrix} = \begin{pmatrix} \dfrac{1}{k_1} & 0 \\ -\dfrac{1+k_1}{k_1(1+k_2)} & \dfrac{1}{1+k_2} \end{pmatrix} \begin{pmatrix} T_i \\ T_o \end{pmatrix} \tag{6}$$

Under the second transmission mode brake Z is separated and clutch C is engaged, the relationship between speed, torque of motor A, B and the speed, torque of the input and output:

$$\begin{pmatrix} n_A \\ n_B \end{pmatrix} = \begin{pmatrix} -k_1 & 1+k_1 \\ k_1 k_2 & 1-k_1 k_2 \end{pmatrix} \begin{pmatrix} n_i \\ n_o \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} T_A \\ T_B \end{pmatrix} = \begin{pmatrix} \dfrac{1-k_1 k_2}{k_1(1+k_2)} & \dfrac{k_2}{1+k_2} \\ -\dfrac{1+k_1}{k_1(1+k_2)} & \dfrac{1}{1+k_2} \end{pmatrix} \begin{pmatrix} T_i \\ T_o \end{pmatrix} \tag{8}$$

Seeing from the transmission diagrams, in the process of switching from the first mode to the second mode, there is no difference in speed between the initiative part and the passivity of the clutch, which gives benefits to the design of the clutch and the life of the clutch enhancing, and especial hashness[18].

Table 2. Parameters table

Parameters	Value	Parameters	Value
Vehicle mass m/kg	2 750	Wheel radius r/m	0.407 6
Engine power P/kW	248	Parameter k_1	1.75
Max speed v/(km • h^{-1})	180	Parameter k_2	3.45

Taking the parameters of a SUV dual-mode hybrid driven vehicle, for example, the parameters are shown in Table 2, and the rotational speed, torque and power characteristics of the program are shown in Fig. 8.

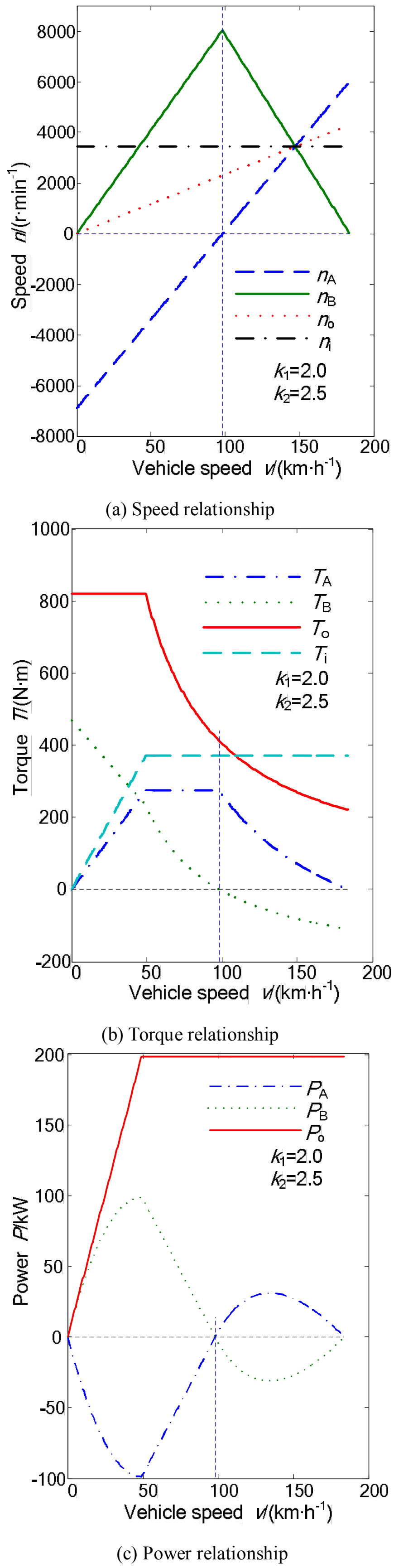


Fig. 8. Speed, torque and power characteristics of program

Figure 8 rotational speed relationship conforms to the set targets (Fig. 3), indicating that in accordance with the above method it can obtain the transmission structure which meets the requirements. The rotational speed relationship figure show that when the engine rotational speed is constant, with the rise of the output rotational speed, the rotational speed of motor *A* reduces under the first model and rotational speed of motor *B* increases. Across the mode switching point, the rotational speed of motor *A* increases and the rotational speed of motor *B* is reduced.

The power diagram shows that under the first mode, motor *A* is a generator, and motor *B* is driving, and vice versa under the second mode. In the first mode, the electric shunt power is huge, and when the vehicle is in low rotational speed and high torque output, motor *A* and motor *B* run in a high-power output state, which easily leads to motor overheating. As the first mode of low rotational speed and high torque output state is not a common vehicle driven state, it should try to reduce the electrical power demand to make the motor power demand of the first mode and second mode more reasonable.

By changing the engine input rotational speed, the rotational speed relationship is obtained as shown in Fig. 9. With the rise of engine rotational speed, the corresponding output rotational speed of the mode switching point also rises accordingly. Corresponding to the same output rotational speed, the engine, the motor *A* and motor *B* can have different rotational speed combinations. Thus it can optimize the working rotational speed of motor *A* and *B* to make the engine work in a more economical speed.

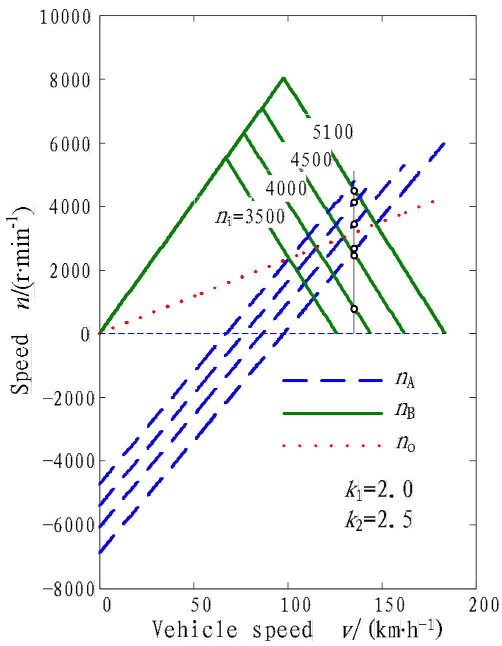


Fig. 9. Speed characteristic of dual-mode under different input speed

The different planetary gear set parameter has great impact on the rotational speed characteristics, and it shows the change of the transmission speed characteristics which is caused by the change of the characteristic parameters k_1 of the planetary gear set in Fig 10. With the increase of k_1, making the mode switching point of the transmission system shift to the right, the maximum rotational speed of motor *B* increases, the maximum rotational speed of motor *A* decreases and the range of output rotational speed narrows; with the increase of k_2, making the mode switching point of the transmission system shift to left, the output rotational speed range widened, but it does not affect the maximum rotational speed of motor *A* and *B* (Fig.11). Therefore, it needs rational allocation for the planetary gear set to make the motor rotational speed at a reasonable range.

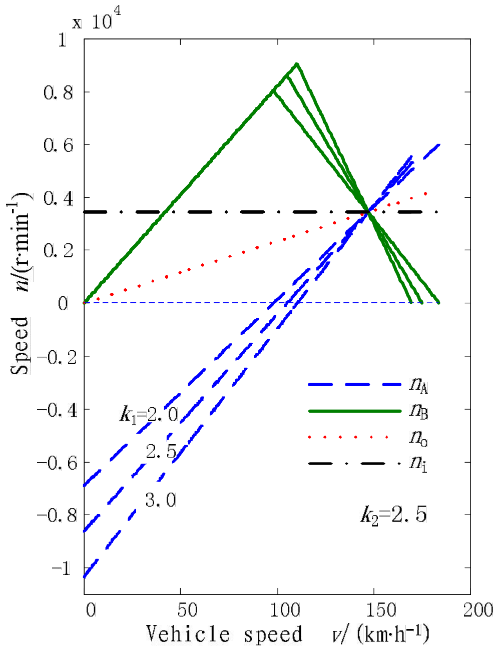


Fig.10. Influence of the first planetary row parameters on speed characteristics

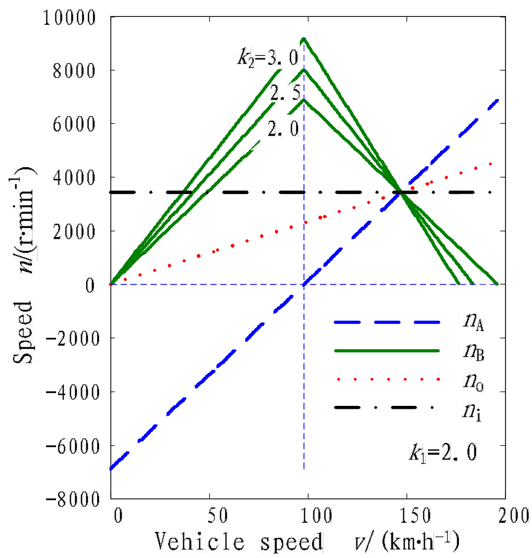


Fig.11. Influence of the second planetary row parameters on speed characteristics

6 Conclusions

(1) In this article, we discuss and reveal the working principle of the multi-mode electro-mechanical variable transmission system. Using the four-quadrant work characteristics of the motor and rotational speed characteristics of the simple internal and external meshing single-star planetary gear set, the design method on the velocity property of two-mode electrical-mechanical hybrid transmission was proposed, and the design method on the scheme of the two-mode electrical-mechanical hybrid transmission was put forward.

(2) Four kinds of dual-mode electromechanical variable transmission system schemes are designed. It has made analysis on the rotational speed, torque and power characteristics about one of these programs. It is obtained: the design program meets the vehicle demand.

(3) The planetary gear set parameter has great impact on the rotational speed characteristic of the electro-mechanical variable transmission system, which affects motor, output rotational speed range and the positions of the mode switching point, so it needs rational allocation for the planetary gear set parameter to make the motor and the rotational output speed meet the vehicle requirements.

(4) When the vehicle is in low rotational speed and high torque output, the electric shunt power is huge, while in the second mode, the motor power is much smaller. So in the parameter matching design it should minimize the motor power demand in first mode as much as possible and raise electric shunt power in the second mode, which can reduce the motor power and enhance the utilization of the motor power within dual-mode, and then enhance the power density of total dual-mode electromechanical compound of variable transmission.

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Biographical notes

LI Hongcai, born in 1970, is currently a PhD in *National Key Lab of Vehicular Transmission*, *Beijing Institute of Technology*, *China.* He received his PhD degree from *Beijing Institute of Technology*, *China*, in 2010. His research interests include vehicular transmission and control technology, test and measurement technology, and hybrid electric vehicle.
Tel: +86-10-68915968; E-mail: armwtank@bit.edu.cn

YAN Qingdong, born in 1964, is currently a professor in *National Key Lab of Vehicular Transmission*, *Beijing Institute of Technology*, *China.* He received his PhD degree from *Beijing Institute of Technology*, *China*, in 1995. His research interests include vehicular system integration, transmission and control technology, and mobile robot technology.
Tel: +86-10-68949096; E-mail: yanqd@bit.edu.cn

XIANG Changle, born in 1963, is currently a professor in *National Key Lab of Vehicular Transmission*, *Beijing Institute of Technology*, *China.* He received his PhD degree from *Beijing Institute of Technology*, *China*, in 2001. His main research interests include vehicular system integration, transmission torsional vibration, and dynamic simulation and experiment, and hybrid electric vehicle.
Tel: +86-10-68913667; E-mail: xiangcl@bit.edu.cn

WANG Weida, born in 1980, is currently a PhD in *National Key Lab of Vehicular Transmission*, *Beijing Institute of Technology*, *China*. He received his PhD degree from *Beihang University*, *China*, in 2009. His main research interests include vehicular dynamics and control, and hybrid electric vehicle.
Tel: +86-10-68918489; E-mail: wangwd0430@163.com