Analysis on the characteristics of compound-split mode powertrain system

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Abstract. In this paper, The rotate speed and torque relationship of the compound-split mode power split device was analyzed, and defined the mechanical point, analyzed the relationship between the power distribution ratio of system and transmission ratio, By using the lever diagram with four nodes, the relative position relations between the mechanical point and Power assembly elements were analyzed which will affect the transmission efficiency of the system, and through the analysis on the characteristic relationship between power elements, with the help of geometry theory to determine the characteristic parameters of planetary gear train, and provides the reference for the configuration design of the dual-mode hybrid system.

1. Introduction

Since Toyota introduced the Prius series electric hybrid model, the research of power-split hybrid powertrain system has been paid more and more attention. In the later stage, GE and Daimler have further promoted the research process in this field by applying dual-mode technology to the vehicles.

The power-split hybrid powertrain system is divided into input-split mode, output-split mode and compound-split mode and series mode. According to the different split modes. In the literature [1-2] has carried on the comprehensive analysis on the efficiency and characteristic of the motor and transmission system about input-split mode and output-split mode, it is concluded that the input-split mode is suitable for the vehicle at low speed condition, the output-split mode reflects the advantage at higher speed.

Relative to the input-split mode, output-split mode, compound-split mode in structure is composed of two groups of planetary gear row, and the two motors are not attached directly to the engine and output shaft, therefore the speeds of two motors can all be zero, and implement two mechanical points. Between the two mechanical points and at the two points, the system has a higher transmission efficiency, so the compound-split mode has a broader high efficiency working area than the previous two modes.

2. Analysis on characteristics of the rotate speed and torque

Building a configuration of compound-split mode, that is combined by two single planetary row PG1 and PG2, each single planetary row has three nodes and two of the three nodes are connected. and the
engine, output shaft, generator/motor MG1, MG2 are connected to the four nodes [3], as shown in the Fig. 1.

**Fig. 1** Compound-split configuration

The design of the configuration and the corresponding four-node lever model are established.

**Fig. 2** Lever diagram with four-nodes

As shown in Fig. 2, the input of configuration is connected to the engine, The two sun gears connected two Generator/Motors respectively and the last point is connected to the output shaft, the node of the output shaft is defined as the base point O, and the length of the base point to the node which connected the engine is as 1. The ratio of the lever length of the output shaft to the MG1 to the lever length of the output shaft to the engine as α. The ratio of the lever length of the output shaft to the MG2 to the lever length of the output shaft to the engine as β, which is shown as negative on the other side of the basis.

The dynamic analysis of the lever model was carried out to obtain the revolving speed balance equation between the components of the powertrain.

\[
\omega_{MG1} = (1 - \alpha) \omega_{out} + \alpha \omega_{En} \\
\omega_{MG2} = (1 + \beta) \omega_{out} - \beta \omega_{En}
\]

\(\omega_{MG1}, \omega_{MG2}, \omega_{En}, \omega_{out}\) are the angular velocity of the generator, the motor, engine and the output shaft respectively.

Ignore the inertia of each moving component, the torque balance equation is obtained by the lever model.

\[
T_{En} (\alpha - 1) - T_{out} \alpha + T_{MG2} (\alpha + \beta) = 0
\]
\[ T_{Eh} (\alpha - 1) - T_{\omega e} + T_{MG2} (\alpha + \beta) = 0 \]  

(4)

\(\omega_{MG1}, \omega_{MG2}, \omega_{En}, \omega_{out}\) are the torque of the generator, the motor, engine and the output shaft respectively.

The power balance of the system satisfies the equation:

\[ P_{batter} = T_{MG1}\omega_{MG1} + \eta T_{MG2}\omega_{MG2} \]  

(5)

Where \(P_{batter}\) is as the output power for the battery pack, and the hybrid electric vehicle battery power models generally appear in the pure electric working mode, which has little influence on the characteristics of powertrain [4], the electrical power balance is represented by the following equation:

\[ T_{MG1}\omega_{MG1} + \eta T_{MG2}\omega_{MG2} = 0 \]  

(6)

\[ \eta = \begin{cases} 
\frac{1}{\eta_{charging}\eta_{discharging}} & T_{MG1}\omega_{MG1} \leq 0 \\
\eta_{charging}\eta_{discharging} & T_{MG2}\omega_{MG2} \leq 0 
\end{cases} \]  

(7)

Where \(\eta_{charging}\) is the Motor efficiency; \(\eta_{discharging}\) is the Generator efficiency.

3. Electrical power characteristic analysis

In the power split system, the power of engine pass through the paths of mechanical and electrical transmission in driving vehicles, due to the power passing through the electric path will be distributed through secondary conversion, which can cause power loss, results in the decrease of system efficiency [5]. In the face of different transmission ratio, the power assigned to the two paths is different, when all the power of the engine is passed to the output shaft by the mechanical path, the system efficiency is the highest, the transmission ratio is called mechanical point at this time. It is obvious that when the rotational speed of one motor is zero and the torque of another motor is zero, the corresponding transmission ratio is mechanical point [6].

The system transmission ratio is represented by the following equation:

\[ \lambda = \frac{\omega_{En}}{\omega_{out}} = \frac{T_{out}}{T_{Eh}} \]  

(8)

For the above configurations, when the rotate speed of the MG1 and MG2 at zero, the power flow passing the system's electric path is zero, and the corresponding two mechanical points are obtained and given as

\[ \lambda_{MP1} = \frac{\omega_{En}}{\omega_{out}} = \frac{\alpha - 1}{\alpha} \]  

(9)

\[ \lambda_{MP2} = \frac{\omega_{En}}{\omega_{out}} = \frac{\beta + 1}{\beta} \]  

(10)
The introduction of a parameter represents the power distribution ratio, the following equation represents the ratio of the power passing the electric path to the power of the engine.

\[ \rho = \frac{P_{\text{elect}}}{P_{\text{in}}} \]

Where \( \rho = \frac{\lambda - \lambda_{\text{MP1}}}{\eta(\lambda_{\text{MP2}} - \lambda)} \)

\[ \rho = \frac{P_{\text{elect}}}{P_{\text{in}}} = \begin{cases} \frac{(\lambda - \lambda_{\text{MP1}})(\lambda_{\text{MP2}} - \lambda)}{\eta(\lambda_{\text{MP2}} - \lambda)} - \lambda_{\text{MP1}} \leq \lambda \leq \lambda_{\text{MP2}} \frac{1}{\lambda} \left( \frac{\lambda - \lambda_{\text{MP1}}}{\eta(\lambda_{\text{MP2}} - \lambda)} \right) - \lambda_{\text{MP1}} \leq \lambda \leq \lambda_{\text{MP2}} \frac{1}{\lambda} \left( \frac{\lambda - \lambda_{\text{MP1}}}{\eta(\lambda_{\text{MP2}} - \lambda)} \right) - \lambda_{\text{MP1}} \leq \lambda \leq \lambda_{\text{MP2}} \end{cases} \quad (11) \]

By using of MATLAB, the relationship between power distribution ratio and system transmission ratio is established as shown in Fig. 3

**Fig. 3** Relationship between electric power and transmission ratio

In the Fig.3: MP1, MP2 is the two mechanical points of the configuration system, the electric power has a limited maximum between two points. In the face of different transmission ratios, the motor has different roles and power flow direction is different [7]. When the transmission ratio is between two mechanical points, \( \lambda_{\text{MP1}} < \lambda < \lambda_{\text{MP2}} \). The generator MG1 is in the working condition, and the motor MG2 is in electric condition. The power of the electric path flows from MG1 to MG2, the system appears power split; when \( \lambda < \lambda_{\text{MP1}} \) or \( \lambda > \lambda_{\text{MP2}} \), MG1 and MG2 work in reverse power direction, MG1 works in electric mode while MG2 works in power generation mode, and the system appears power cycle phenomenon. When the power appears in circulation, the electric path has no power transmit to the output shaft, that is, the power in the electric path will not be used to drive the vehicle. At this time, the power of the engine may well exceed the power required for the whole vehicle, which greatly reduces the system transmission efficiency.

In addition, when the system transmission ratio is too small or too large, which will cause electric power distribution bigger, and that will lead to the motor rate increase, which matched to the system. And the motor size will be bigger, which can bring about the motor current increase and the energy loss of the power converter, increase more difficult of the vehicle layout, which will increase the vehicle quality and thus reduce the fuel economy of the vehicle. So we should select the range of transmission ratio reasonably according to the actual demand of operating condition, so as to facilitate the selection of motor power.
4. **Analysis of compound-split configuration**

To the compound-split configuration, when MG1 and MG2 rotate speed is zero, two mechanical points appear [8].

Through the analysis on the lever mode, according to the position relationship among engine, the output shaft and two generator/motor which are connected to the four nodes on the lever model to judge the transmission ratio and the area of the system corresponding to the two mechanical points. When $\lambda > 1$, the speed of the vehicle is decelerated; When $\lambda < 1$, the speed of the vehicle is over-speed [9]. Such as lever model is shown in the Fig. 4, with a dotted line identify the speed of MG1 and MG2 at zero respectively, the corresponding rotate relationships of the nodes which the engine, output shaft connected to. In the Fig. 4 a, when MG1 and MG2 speed at zero, respectively, the engine speed is greater than the output shaft speed, so the two mechanical points are greater than 1, both in the reduction range, if the arrangement is adopted, the vehicle will has no corresponding higher efficient transmission area at high speed; In the same way, in the Fig. 4 b, two mechanical points are less than 1, and in overdrive range, if the arrangement is made ,which will cause the power passing electrical path is too large, the system efficiency is too low when the vehicle drives at intermediate speed; in the Fig. 4 c ,a mechanical point is greater than 1, and another mechanical point is less than 1, which makes the vehicle possess higher system transmission efficiency when driving at low speed and high speed conditions, using this arrangement, efficient area will be broader than the before both, and conform to the normal condition that the vehicle operates in.

![Fig. 4 Three lever diagrams](image)

5. **Conclusion**

The relationship was established among the rotational speed, torque of the powertrain components by lever model analysis, it was obtained that the relationship between the power split ratio and the system transmission ratio, by analyzing the characteristics of the compound-split configuration, and it was obtained that the relationship among the motor power and the system transmission ratio and Power distribution ratio, which provided the basis for the motor power matching. By analyzing the location selection of the mechanical points and the powertrain components, and obtained the different layout schemes and system transmission efficiency, which provided a reference for the configuration design of hybrid transmission mechanism using the compound-split mode. and the characteristic parameters of the planetary row was optimized, and the optimal parameters was obtained from the mathematical point of view, which also provided an effective basis for the matching of power system.

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