Design of A Planetary Gear Mechanism of A Seven-speed Automatic Transmission Based on the Lever Method

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Abstract. The existing six-speed automatic transmission of Toyota AB60E has the shortcomings of large number of transmission actuators and complicated structure. The paper first uses the lever method to analyze the lever diagram of each gear of the transmission. And then, based on the six-speed automatic transmission of Toyota AB60E, a new seven-speed automatic transmission is designed. The lever method is used to analyze the speed of each component of the newly designed one and the relative speed of its shift actuators and planetary gears. Finally, the external torque of the device and the internal torque of each component are calculated. The results show that, with the same structure parameters of the planetary row, the number of shift actuators of the new transmission decreases to 6 and the gears increase to 7. The transmission ratio between gears is closer, and the overall performance is better than that of the transmission of AB60E. The automatic transmission of planetary gears can be designed quickly by the lever method, and the kinematics and dynamics analysis can be carried out.
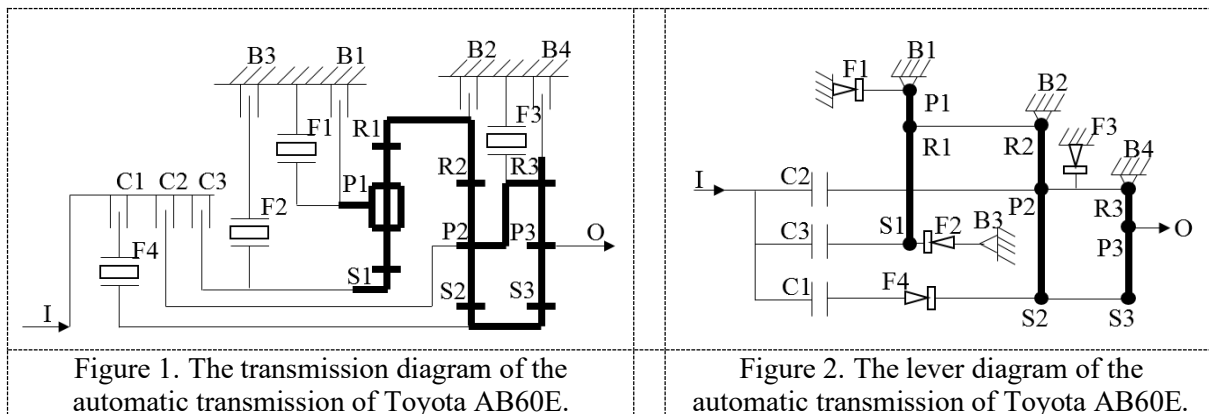
1. Introduction

The automatic transmission is one of the most complex parts of automobile technology [1], and its technology level has a great impact on the automobile performance, such as the power matching, the fuel consumption, the emission, the acceleration performance, the maneuverability and so on. Therefore, the mainstream automobile companies in the world are committed to the research and development of the automatic transmission [2-3]. Because of the complexity of planetary gear mechanism, the speed, the rotation direction, the transmission ratio of each component, and the analysis of transmission force and torques of each component have been the research difficulties [4-5]. The common analysis methods of the planetary gear mechanism are the mathematical analysis method and the geometric graphic method [6-7]. The mathematical analysis method uses a series of linear equations to express the characteristics of the mechanism and some calculation software like MATLAB to analyze. Although the results can be obtained, the internal relationship of the parameters is not intuitive enough. The geometric graphic method is based on graphics, which can visually display the working characteristics of every planetary gear row, so it is widely used in the analysis and design of the automatic transmission. In various graphic methods such as the vector diagram, the contour diagram and the lever diagram, the lever diagram transforms the planetary gear train into a lever system and elements in the planetary gear train into corresponding nodes on the lever [8]. Compared with the mathematical analysis method, it is more intuitive, more visual, faster and clearer. Therefore, based on the analysis of the six-speed automatic transmission of Toyota AB60E [9], this paper designs a seven-speed planetary gear automatic transmission with the lever method, then carries out the kinematics and dynamics analysis, and finally compares the designed seven-speed transmission with the six-speed transmission of AB60E to illustrate the advantages of each index of the newly designed one.

2. The transmission diagram and the lever diagram of the six-speed automatic transmission of Toyota AB60E

2.1. The transmission diagram of the six-speed automatic transmission of Toyota AB60E
As shown in Figure 1, the six-speed automatic transmission of Toyota AB60E is made up of 3 planetary gears. 6 forward gears and 1 reverse gear need 11 shift actuators, namely 3 clutches C1/C2/C3, 4 brakes B1/B2/B3/B4 and 4 one-way clutches F1/F2/F3/F4. Among them, the front planetary row is single row and double stage, the middle planetary row and the rear planetary row are single row and single stage, and the corresponding sun gear, the planetary frame and the gear ring are expressed by "S", "P" and "R" respectively. Teeth numbers of the sun gear and the gear ring in the planetary row are $Z_{S1} = 43$, $Z_{R1} = 91$, $Z_{S2} = 33$, $Z_{R2} = 78$, $Z_{S3} = 27$, $Z_{R3} = 62$, respectively. The front planetary gear ring is connected with the middle planetary gear ring, the middle planetary row planetary frame is connected with the rear planetary gear ring, the middle planetary row sun gear is connected with the rear planetary row sun gear, and the rear planetary row planetary frame is used as an output component. The connection of each shift actuator is shown in the following figures.

| Figure 1. The transmission diagram of the automatic transmission of Toyota AB60E. | Figure 2. The lever diagram of the automatic transmission of Toyota AB60E. |

2.2. The lever diagram of the six-speed automatic transmission of Toyota AB60E
Figure 2 is a lever diagram corresponding to the six-speed automatic transmission of Toyota AB60E. Each planetary row is a lever. The three points on the lever represent the sun gears S1/S2/S3, the planetary frames P1/P2/P3, and the gear rings R1/R2/R3 respectively. The planetary frame of the single-row single-stage planetary row is in the middle of the three points on the lever, while the gear ring of the single-row double-stage planetary row is in the middle of three points on the lever. With reference to Figure 1, draw three planetary rows, eleven shift actuators, one input shaft, one output shaft, and some corresponding wires between them in turn. The completed lever diagram is shown in Figure 2.

According to the literature [9], most gears of the transmission need three or more shift actuators to work, which is a challenge to the design of the hydraulic system and the control system. Moreover, the one-way clutch is used from the first to the fourth gears and in the reverse gear, which makes the structure of the transmission complicated. Three planetary rows and eleven shift actuators can only realize six forward gears and low design efficiency. Based on this transmission, a new seven-speed transmission is designed according to the principle of the lever diagram, in which most of the components are simplified. The detailed structure is described in section 3.

3. The transmission diagram and the lever diagram of the seven-speed automatic transmission

3.1. The transmission diagram and the overall lever diagram of the newly designed seven-speed automatic transmission
Figure 3 is the transmission diagram of the seven-speed automatic transmission designed in this paper. It has 3 planetary row structures compared with that of Toyota AB60E. However, there are only 6

actuators, namely 4 clutches C1/C2/C3/C4 and 2 brakes B1/B2, no one-way clutch. Actuators are reduced by half and a forward gear is added. The specific connection mode is shown in the above figures, and the overall lever diagram of the seven-speed automatic transmission based on the lever method is shown in Figure 4.
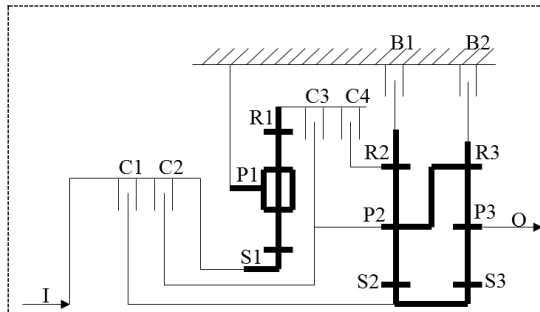
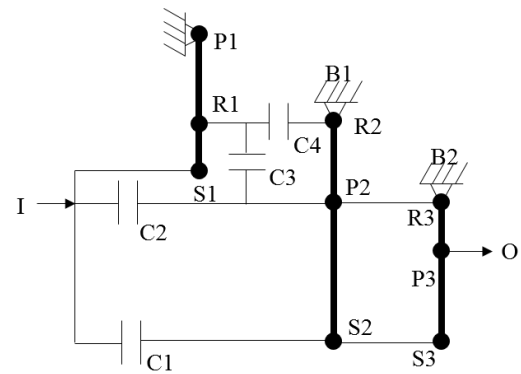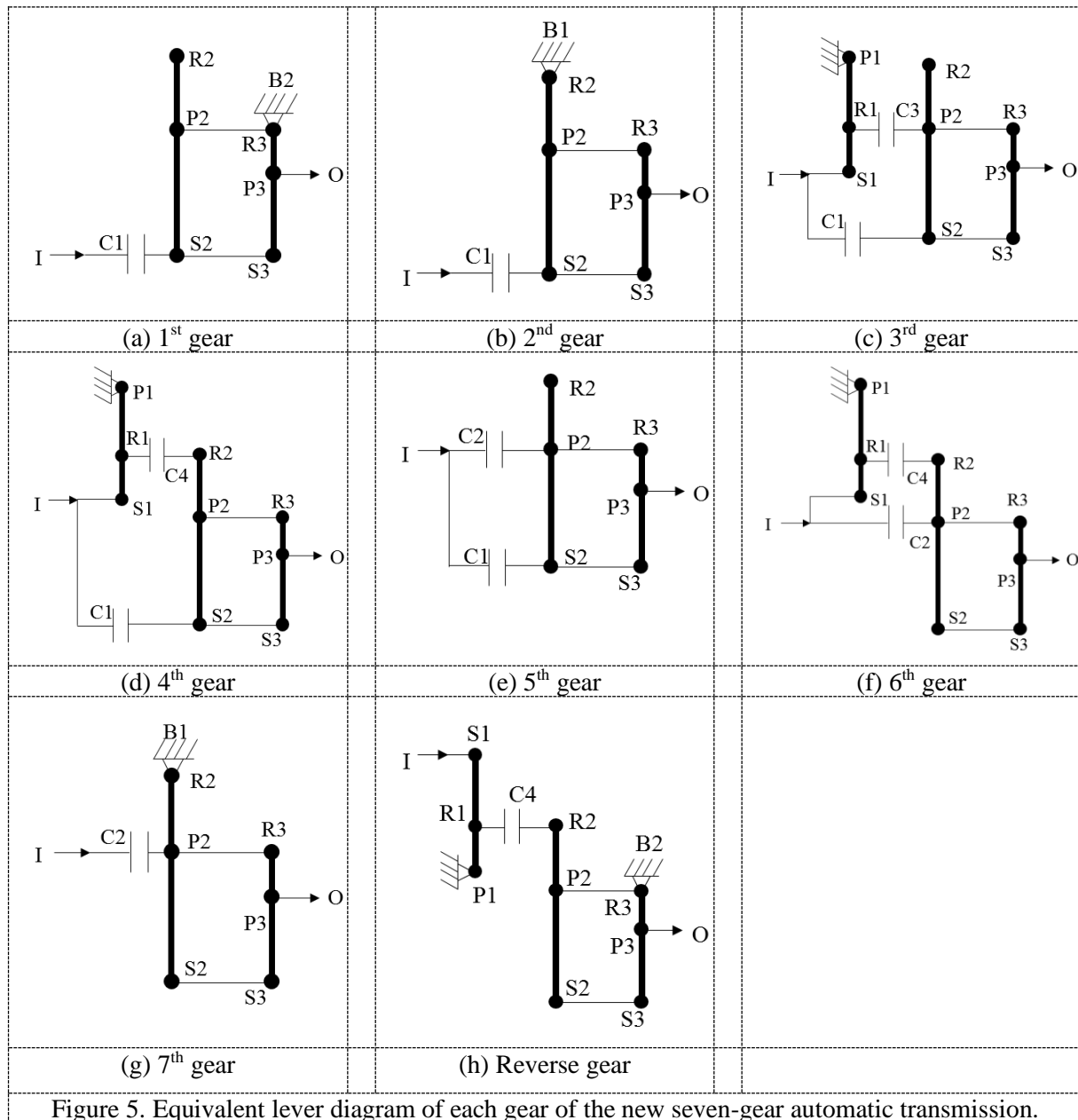| Figure 3. The transmission diagram of the new seven-speed automatic transmission.	Figure 4. The overall lever diagram of the new seven-speed automatic transmission.

3.2. The lever diagram of each gear of the new seven-speed automatic transmission
Table 1 is a list of the gear combination elements designed for the new seven-speed automatic transmission. Only two shift actuators are needed for each gear. The design of the hydraulic system is simplified and the shift efficiency of each gear is improved.

Table 1. Table of the gear combination elements for the new seven-speed automatic transmission.

Gears	Shift actuators					
	Clutches				Brakes	
	C1	C2	C3	C4	B1	B2
1	●					●
2	●				●	
3	●		●			
4	●			●		
5	●	●				
6		●		●		
7		●			●	
R				●		●

According to Figure 4 and Table 1, the transmission lever diagram of each gear is drawn in Figure 5. If a planetary row is not involved in the power transmission, it is not indicated in the corresponding gear diagram.
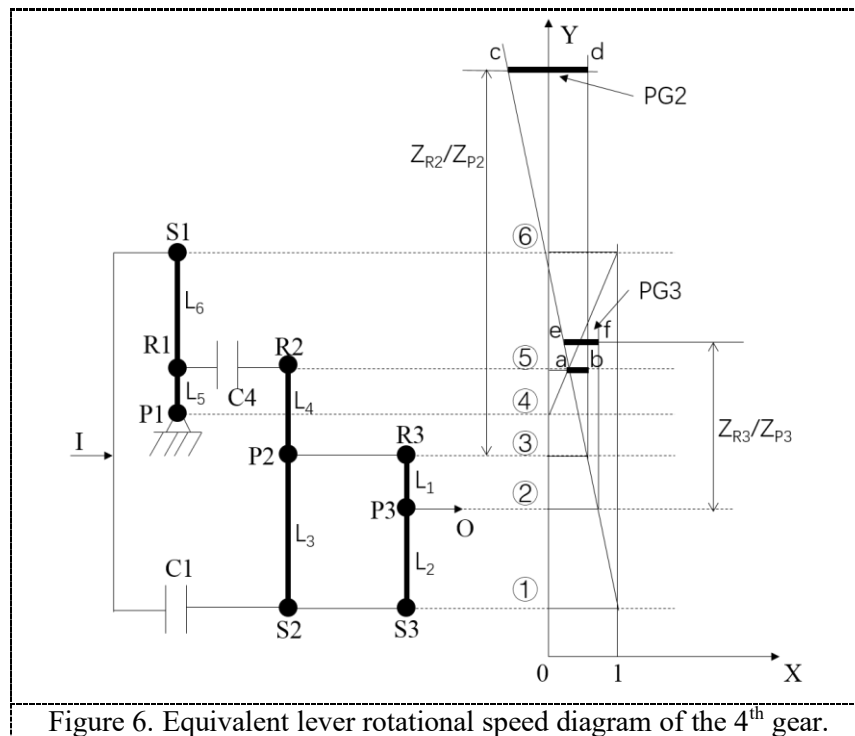
Figure 5. Equivalent lever diagram of each gear of the new seven-gear automatic transmission.

4. Kinematics analysis of the new seven-speed automatic transmission

4.1. Rotational speed analysis of each gear

To design a new automatic transmission and carry out its kinematics analysis, it is necessary to know the rotational speed of each component and each planetary wheel in the planetary row, the relative rotational speed between the friction plate and the steel plate in the shifting actuator in the separated state, as well as the calculation of the transmission ratio of each gear position.

In this paper, we take the complicated 4th gear of the new automatic transmission as an example. The three planetary rows of the gear are all involved in the power transmission. According to the equivalent lever diagram of the 4th gear, the three planetary rows in this gear form a six-node lever, and the six nodes represent the six independent components: the input component S2 and S3 as in ①, the output component P3 as in ②, the connection component P2 and R3 as in ③, the component P1 as in ④ , the

connection component R1 and R2 as in ⑤, and the input component S1 as in ⑥. Set these six nodes on the corresponding rectangular coordinate axis XOY, as shown in Figure 6.

Figure 6. Equivalent lever rotational speed diagram of the 4th gear.

Make a vertical line parallel to axis Y with X = 1. The speed of input component ① and ⑥ is + 1. Point ④ on axis Y is connected with the shell as a fixed point, and the speed is 0. Connect the fixed point and the input point in turn, that is, connect the two points (1, Y⑥) and (0, Y④) and the other two points (a, ⑤) and (1, ①) to get two corresponding speed lines. Through the horizontal straight line of each node intersecting with the above speed lines of the corresponding point, values on axis X of each intersection point represent the speeds of each component. The positive and negative values of X represent the direction of each component. For example, the vector corresponding to ⑤a represents the speed of the components R1 and R2. Other gears can get the corresponding speed curve by similar methods, and the speed of each component also can be analyzed.

4.2. Relative rotational speed of the united components in each gear
The relative rotational speed between the friction plate and the steel plate in the separated state in each gear is equal to the difference of the rotational speed between the two basic components connected to them. For example, in the 4th gear, clutch C3 is arranged between R1 and P2. As can be seen from Figure 6, the rotational speed of component R1 is the value of point a on axis X and that of component P2 is the value of point b on axis X, so the relative rotational speed between the steel plate and the friction plate of the clutch C3 is the corresponding length of the line segment ab.

4.3. Relative rotational speed of the planetary gear in each gear
For example, we need to find the relative speed of the planetary gear PG2 of the planetary row 2 in the 4th gear. The planetary frame P2 in the planetary row 2 corresponds to the rotational speed point of the component point ③. Passing through this rotational speed point, a line paralleled to axis Y is made. Then draw a vertical line Z_{R2}/Z_{P2} away from point ③ along Y axis (away from S2), and the rotational speed point of the planetary gear PG2 is point d. When the horizontal line passing through point d

intersects the speed line of the 4th gear at point c, the corresponding vector of cd is the relative speed of the planetary gear PG2. Similarly, the relative speed of planetary gear PG3 of the planetary row 3 can be calculated as ef, as shown in Figure 6.

4.4. Calculation of the transmission ratio of each gear

The transmission ratio of each gear can be calculated by triangles and trapeziums formed by the rotational speed lines of each component point in the lever rotational speed diagram according to the triangle similarity principle. For example, the transmission ratio of the 4th gear is the rotational speed ratio of the input component ① with that of the output component ②. According to the principle of lever method, we unified the corresponding sizes in the geometric figure. Let the characteristic parameters of the three planetary rows be $K_1 = Z_{R1}/Z_{S1}$, $K_2 = Z_{R2}/Z_{S2}$, $K_3 = Z_{R3}/Z_{S3}$. Taking the planetary row 3 as the reference size, the lengths of each segment in Figure 6 are $L_1=1$, $L_2= K_3$, $L_3=1+K_3$, $L_4=(1+K_3)/K_2$, $L_5=1$, $L_6= K_1-1$. According to the principle of triangle similarity, the transmission ratio of the 4th gear can be solved.

$$i_4 = n_I/n_O = (K_1-1)(K_2+1)(K_3+1)[K_2(K_1+K_3-1)+(K_1-1)(K_3+1)]^{-1} \tag{1}$$

According to the teeth number of each gear in the planetary row, the transmission ratio of each gear can be calculated by the same method. The transmission ratios of Toyota AB60E and the new seven-speed automatic transmission are calculated as shown in Table 2. It can be seen that the transmission ratio range of the designed seven-speed automatic transmission is basically the same as that of the transmission of Toyota AB60E, but the transmission ratio between adjacent gears is closer, and the ride comfort of the car will be better. On this basis, the kinematics analysis namely the moment analysis of the designed seven-speed automatic transmission, is further carried out. Details can be found in the next section.

Table 2. Comparison table of the transmission ratio of each gear.

Gears	The new seven-speed automatic transmission	The automatic transmission of Toyota AB60E
1	3.300	3.333
2	1.961	1.960
3	1.580	1.353
4	1.348	1.000
5	1.000	0.728
6	0.726	0.588
7	0.582	
R	2.950	3.061

5. Dynamic analysis of the new seven-speed automatic transmission

5.1. External torques of the planetary mechanism

Take the 4th gear as an example. Shown in Figure 7, according to the principle of force balance, $M_I+M_O+M_B=0$, and $M_O =-iM_I$, $M_B=(i-1) M_I$ can be obtained. Therefore, the output torque and the braking torque of the 4th gear are respectively as followed:

$$M_O=-M_I(K_1-1)(K_2+1)(K_3+1)[K_2(K_1+K_3-1)+(K_1-1)(K_3+1)]^{-1} \tag{2}$$

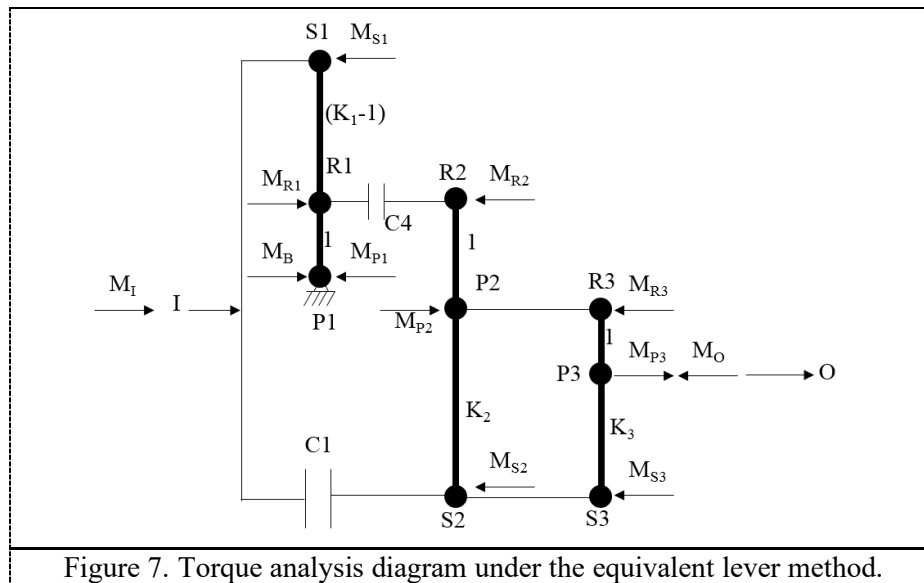$$M_B=M_I K_2 K_3(K_1-2)[K_2(K_1+K_3-1)+(K_1-1)(K_3+1)]^{-1} \tag{3}$$

Figure 7. Torque analysis diagram under the equivalent lever method.

5.2. Internal torque of the planetary rows

The internal torque of the planetary rows refers to the acting torque of the planetary gears of every planetary row on the sun gears, the gear rings and the planetary frames of the planetary row. Starting from a component whose external torque is known and subject to only one internal torque, the internal torque on the component is opposite to the external one, and the size of the two torques are the same. Next, the internal torques of each component are solved in turn.

Therefore, calculation starts from planetary row 1. $M_{P1}=-M_B=(1-i)M_I$. From the principle of force balance of the lever, the internal torque of the sun gear can be calculated: $M_{S1}= M_{P1}/(K_1-1)= (1-i)M_I/(K_1-1)$. The internal torque of gear ring is $M_{R1}= -K_1M_{S1}= (i-1)M_I K_1/(K_1-1)$.

Planetary row 2: gear rings R2 and R1 are connected by clutch C4, so $M_{R2}= -M_{R1}=(1-i)M_I K_1/(K_1-1)$. From the principle of force balance of the lever, the internal torque of the sun gear can be calculated. $M_{S2}=M_{R2}/K_2=(1-i)M_IK_1/[K_2(K1-1)]$.

The internal torque of the planetary frame is $M_{P2}=-M_{R2}(K_2+1)/K_2=(i-1)M_I K_1(K_2+1)/[K_2 (K_1-1)]$.

Planetary row 3: gear rings R3 is connected with the planetary frame P2. The internal torque of gear ring R3 is $M_{R3}=-M_{P2}=(1-i)M_I K_1(K_2+1)/[K_2 (K_1-1)]$. From the principle of force balance of the lever, the internal torque of the sun gear S3 can be calculated. $M_{S3}=M_{R3}/K_3=(1-i)M_I K_1(K_2+1)/[K_3K_2 (K_1-1)]$. The internal torque of the planetary frame P3 is $M_{P3}=-M_{R3} (K_3+1)/K_3=(i-1)M_I K_1(K_2+1)(K_3+1)/[K_3K_2 (K_1-1)]$.

Each component torques of other gears can also be calculated by this method.

6. Conclusion

Based on the lever method, the lever diagram of the six-speed automatic transmission of Toyota AB60E and the lever diagram of each gear are analyzed. On this basis, a new type of seven-speed automatic transmission is designed. Under the condition of keeping the parameters of the planetary row unchanged, the number of shift actuators of the new transmission is reduced to 6, and the gears are increased to 7. The transmission ratio between gears is more compact, which can improve the matching property between the automatic transmission and the automobile. On this basis, the lever method is used to analyze the kinematics and dynamics of the newly designed automatic transmission.

According to the transmission diagram of the new type transmission, the corresponding overall lever diagram is drawn, and the lever diagram of each gear is designed. Taking the more complex 4th gear as an example, in the coordinate system XOY, according to the principle of geometric similarity, the speed of each component, relative speed of the shifting actuator in the separated state and the transmission

ratio of each gear can be quickly obtained. At last, the external torque of the planetary mechanism and the internal torque of each component of the new automatic transmission are calculated.

The lever method, which is intuitive, simple and fast graphical, is of great significance to the design of the new planetary-gear automatic transmission.

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