Due to the reason of pollution-free, electric motorcycle become more and more popular in city traffic. The purpose of this work is to propose a design methodology for the invention of planetary gear automatic transmissions for electric motorcycles. First, applying the check list method (combining and extending methods), the design concepts are proposed. Then, based on the train value equation of planetary gear train, we derive reduction-ratio equations of these planetary gear automatic transmissions. In this paper, five new design concepts including three 3-speed and two 4-speed are synthesized. Three examples of the kinematic design of planetary gear automatic transmissions are accomplished to illustrate the design methodology.

**Keywords:** automatic transmission, check list method, kinematic design, planetary gear train.
1. INTRODUCTION

Thanks to the advantage of being light weight, cheap and fast-moving, motorcycles have become the most popular traffic vehicles. The change speed gear drives of motorcycles can be manual or automatic. The automatic transmissions of motorcycles can be the ordinary gear trains, planetary gear trains, and continuously variable transmissions (CVTs) shown in Fig. 1.

Electric motorcycles are pollution-free and hence become more and more popular in city traffic. The purpose of this work is to propose a systematic approach for the invention of planetary gear type automatic transmissions with 3 or 4 speeds. First, by referring to such related patents [1–4], the studies on kinematics of planetary gear trains [5–10], and the studies on the creative design of mechanical devices [11–14], new planetary gear type automatic transmissions with 3 or 4 speeds can be synthesized. In this paper, five new design concepts including three 3-speed and two 4-speed are synthesized. Furthermore, three examples of the kinematic design of planetary gear type automatic transmissions are presented to illustrate the design methodology. Based on the proposed methodology, all planetary gear type automatic transmissions can be synthesized. The results in this paper will contribute to electric motorcycle engineering.

2. AUTOMATIC TRANSMISSION

2.1. Three-Speed Automatic Transmission for Motorcycles

The drive system of the planetary gear type automatic transmission is composed of planetary gear speed changer and ordinary gear reducer. Figure 2 shows a 3-speed automatic transmission which is used in Honda motorcycle. The 3-speed automatic transmission is composed of a planetary gear train, an ordinary gear train, and several clutches (including 3 centrifugal clutches and 2 one-way clutches). Its planetary gear mechanism has 2 speeds and ordinary gear mechanism has 1 speed.

(a) 1st speed: When the engine speed reaches the preset level, the 1st centrifugal clutch C1, one-way clutch Owcl, and one-way clutch Owcl2 are engaged. The sun gear of planetary gear train is then fixed by the one-way clutch Owcl. The driving power is transmitted to the chain device via the ring gear, planet gear, and arm of the planetary gear train. It follows the output axle via the one-way clutch Owcl2 and two reduction gear pairs, its reduction ratio being 22.236.
2.1. Three-Speed Automatic Transmission for Vehicle

Figure 2 shows a three-speed automatic transmission which is used in Mitsubishi vehicle (Lancer). The three-speed automatic transmission is composed of a planetary gear train and several clutches (including 1 centrifugal clutch, 1 one-way clutch, and 2 brakes). Figure 2a shows its corresponding kinematic skeleton and Figure 2b shows its clutch sequence and reduction ratios.

(a) 1st gear: When automatic transmission is at 1st speed, the clutch C1 and one-way clutch Owcl are engaged. The sun gear 3 of planetary gear train is then adjacent to input shaft by clutch C1, planet arm 5 is fixed by the one-way clutch Owcl, and ring gear 5 is adjacent to output shaft. Its reduction ratio is 13.696.

(b) 2nd gear: With the boosting of engine speed, the 2nd centrifugal clutch C2 engages, the one-way clutch Owcl separates, and sun gear of planetary gear train is then unlocked. The planetary gear train rotates together. The driving power is transmitted to the chain device via the planetary gear train, then to the output axis via the one-way clutch Owcl, and two reduction gear pairs, and its reduction ratio is 13.696.

(c) 3rd gear: If the engine speed is increased again, the 3rd centrifugal clutch C3 engages and the one-way clutch Owcl separates. The driving power is transmitted to the chain device by the planetary gear train, then to the output axle via the 3rd centrifugal clutch C3 and two reduction gear pairs, and its reduction ratio is 8.478.

2.2. Four-Speed Automatic Transmission for Vehicle

Figure 3 shows a four-speed automatic transmission which is used in Mitsubishi vehicle (Lancer). The four-speed automatic transmission is composed of a planetary gear train and several clutches (including 3 clutches, 1 one-way clutches, and 2 brakes). Figure 3a shows its corresponding kinematic skeleton and Figure 3b shows its clutch sequence and reduction ratios.

(a) 1st speed: When automatic transmission is at 1st speed, the clutch C2 and one-way clutch Owcl are engaged. The sun gear 2 of planetary gear train is then adjacent to input shaft by clutch C2, planet arm 4 is fixed by the one-way clutch Owcl, and ring gear 5 is adjacent to output shaft. Its reduction ratio is 2.846.

(b) 2nd speed: When the engine speed reaches the preset level, the brake B3 engages, the one-way clutch Owcl separates. The sun gear 2 of planetary gear train is also adjacent to input shaft by clutch C2, sun gear 3 is fixed by brake B3, and ring gear 5 is adjacent to output shaft. Its reduction ratio is 1.581.
Fig. 3. Four-speed automatic transmission for Mitsubishi vehicle (Lancer).

(a) Kinematic skeleton  (b) Clutch sequence and reduction ratios

<table>
<thead>
<tr>
<th></th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>B3</th>
<th>B4</th>
<th>Owc4</th>
<th>Reduction ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Speed (D,2)</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>2.846</td>
</tr>
<tr>
<td>1st Speed (L)</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>2.846</td>
</tr>
<tr>
<td>2nd Speed (D)</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>1.581</td>
</tr>
<tr>
<td>3rd Speed (D)</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4th Speed (D)</td>
<td></td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>0.685</td>
</tr>
<tr>
<td>Reverse Speed</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>-2.176</td>
</tr>
</tbody>
</table>

(c) 3rd speed: With the boosting of engine speed, the clutches C2, C3 and C4 engage and brake B3 separates. The planetary gear train rotates together. Its reduction ratio is 1.0.

(d) 4th speed: If the engine speed is increased again, the clutches C2 and C3 separate and brake B3 engages. The planet arm 4 of planetary gear train is adjacent to input shaft by clutch C4, sun gear 3 is fixed by the brake B3, and ring gear 5 is adjacent to output shaft. Its reduction ratio is 0.685.

(e) Reverse speed: When automatic transmission is at reverse speed, the clutch C3 and brake B4 engage. The sun gear 3 of planetary gear train is adjacent to input shaft by clutch C3, planet arm 4 is fixed by the brake B4, and ring gear 5 is adjacent to output shaft. Its reduction ratio is $-2.176$.

3. CLUTCHES

Generally speaking, the automatic transmission for motorcycle includes the shifting control devices (centrifugal clutches), planetary gear train, and one way clutch. The centrifugal clutch can be roughly divided into two categories: (1) radial centrifugal clutch, shown in Fig. 4, (2) axial centrifugal clutch, respectively shown in Fig. 5. One-way clutch which is consist of outer ring, rollers, inner ring, and spring (not shown). For the structure shown in Fig. 6a, the rotating speed of outer ring is larger than the rotating speed of inner ring, it is in the state of separating and represented as Fig. 6c. For the structure shown in Fig. 6b, the rotating speed of inner ring is larger than the rotating speed of outer ring, it is in the state of engaging and represented as Fig. 6d.
4. TRAIN VALUE EQUATION

A planetary gear train is a gear train contains at least one gear (planet) which is required to rotate above its own axis and another axis. There are numerous design concepts of planetary gear trains. This paper has chosen the non-coupled planetary gear trains to act as the reference basis for our design of the planetary gear type automatic transmissions. Figures 7a and 7b are five-bar planetary gear trains, and Figs. 7c, 7d, and 7e are six-bar planetary gear trains.

For a planetary gear train, let us denote the first sun gear as \( i \), the ring gear as \( j \), and the carrier as \( k \), respectively. The relationship among \( \omega_i \), \( \omega_j \), and \( \omega_k \) can be expressed as

\[
\omega_i - \xi_{ji} \omega_j + (\xi_{ji} - 1) \omega_k = 0,
\]

where \( \xi_{ji} \) is the train value of ring gear \( j \) to sun gear \( i \). The train value \( \xi_{ji} \) be positive sign, if positive rotation of \( \omega_k \) produces positive rotation of \( \omega_{jk} \); and \( \xi_{ji} \) be negative sign, otherwise. For the planetary gear train
shown in Fig. 7a, the train circuit 2-3-5-4-2 contains sun gear 2, sun gear 3, and carrier 4. Its train value
equation and train value $\xi_{32}$ can be expressed as

$$\omega_2 - \xi_{32} \omega_3 + (\xi_{32} - 1) \omega_4 = 4,$$

$$\xi_{32} = -\frac{Z_3 \times Z_5}{Z_5 \times Z_2} = -\frac{Z_3}{Z_2} < 0.$$  (2)

\section*{5. INNOVATIVE DESIGN}

In this paper, we choose the better planetary gear trains for the design automatic transmission for electric
motorcycles. Combine with the one-way clutch and the centrifugal clutch and by apply the check list
method, to conceive the innovative concepts of planetary gear type automatic transmissions for electric
motorcycles.

\subsection*{5.1. Osborn’s Check-List Method}

Osborn was called originator of modern creative science. He proposed many creative methods; one of them
is Check-list method. In his book \textit{Applied Imagination}, he listed 75 questions that could be used to check
for creativity. Some people summarize the check-list from the 75 to 9 items. The common 9 items are:

1. Reverse
2. Transfer
3. Combine
4. Change
5. Extend
6. Enlarge
7. Reduce
8. Substitute
9. Rearrange

When we use the Osborn check-list method to create new ideas and designs, we have to make sure that the
creations can be used to our advantage instead of just for the sake of invention. Therefore, we must create
an innovation which can bring better performance than the current status.

\subsection*{5.2. Design Constrains}

After choosing the planetary gear train, the innovative design can be carried out on the three-speed (or four-
speed) automatic transmissions. On conceiving the feasible design concept, the design constrains of the
automatic transmissions should be taken into consideration, so as to make the composed mechanism to meet
requirements. In this paper, the automatic transmission for electric motorcycle has the following design
constrains:

1. It must possess the automatic shift function that can replace computer control, which belongs to
   mechanical automatic shift mechanism.
2. It needs to possess 3-speed (or 4-speed) automatic shift function.
3. The centrifugal clutch needs to adjust its elasticity setting value and control its engaging order.

4. Considering the effect of output axle, the characteristic of one-way clutch is that the fast one-way clutch acts as the output; considering the effect of input axle, the slow one-way clutch acts as the input.

5.3. Innovation Design
First, we propose a design concept, shown in Fig. 8, to design a planetary gear type automatic transmission. The automatic transmission is coupled by one planetary gear speed changer and one ordinary gear reducer. The planetary gear speed changer must have three (or four speeds) and the ordinary gear reducer just has only one speed. The total reduction ratio of the planetary gear type automatic transmission is $R_{P} \times R_{O}$.

5.3.1. Three-speed planetary gear speed changer
Shown in Fig. 2 is the automatic three-speed changer with planetary gear train. But, in that case, only two speeds are obtained by planetary gear train. Applying the combining method of check list, we combine the
centrifugal clutches, planetary gear train, and one-way clutches to design the planetary gear speed changers. Figure 9 shows the design concept of this invention.

Then, by the changing methods of check list, some changing locations of one-way clutches and centrifugal clutches, it will enlarge the original two gear positions (shown in Figs. 2a and 2b to three gear positions. Figure 10a shows the kinematic structure of planetary gear speed changer including one planetary gear train, two one-way clutches, and two centrifugal clutches. According to the substituting method of check list, the planetary gear trains shown in Fig. 7 are substituted by the planetary gear trains shown in Figs. 7b and Fig. 7e. Two planetary gear speed changers are synthesized shown in Figs. 10b and 10c. These two planetary gear speed changers also include one planetary gear train, two one-way clutches, and two centrifugal clutches.

5.3.2. Four-speed planetary gear speed changer
By the transferring method of check list, the planetary gear train used in four-speed automatic transmission (shown in Fig. 3) can be transferred to design the four-speed automatic transmission for electric motorcycle. Then, by the changing method of check list, some change locations of its one-way clutches and centrifugal clutches, the planetary gear train (shown in Fig. 3) also possesses four gear positions. Figure 11a shows the kinematic structure of four-speed planetary gear speed changers including one planetary gear train, three one-way clutches, and three centrifugal clutches. Then, according to the substituting method of check list, the planetary gear train shown in Fig. 11a is substituted by the planetary gear trains shown in Fig. 7d. One new four-speed automatic transmission is synthesized shown in Fig. 11b. The four-speed planetary gear speed changer also includes one planetary gear train, three one-way clutches, and three centrifugal clutches.
Table 1. Reduction ratio’s requirements of invention 1.

<table>
<thead>
<tr>
<th>Speeds</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction ratios</td>
<td>17.6</td>
<td>11</td>
<td>6.6</td>
</tr>
<tr>
<td>Reduction ratios of planetary gear changer</td>
<td>1.6</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Spacing of speeds</td>
<td>1.6</td>
<td>1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Fig. 12. Three gear positions of invention 1.

6. KINEMATIC DESIGN

By fixing the different link and collocating the one-way clutches and centrifugal clutch, we can design the automatic transmissions for electric motorcycles. Since the planet gears in inventions 2 and 5 are compound gears, they are difficultly to be manufactured and assembled. Hence, we only choose inventions 1, 3, and 4 as example.

6.1. Three-speed automatic transmissions

**Invention 1.** For a three-speed automatic transmission for electric motorcycle to have the reduction ratios from 17.6 to 6.6 and the spacing of adjacent speed is constant. Table 1 shows the reduction ratio’s requirements of this three-speed automatic transmission.

The three-speed automatic transmission consists of one three-speed planetary gear speed changer and one ordinary gear reducer. According to Table 1, in this design, the reduction ratio of ordinary gear reducer is identified as $R_{r(O)} = 11$. Hence the reduction ratios of three-speed planetary gear speed changer are 1.6, 1 and 0.6.

For a planetary gear speed changer shown in Fig. 10a, its train value $\xi_{ji} < 0$. According to Eq. (1), the reduction ratios of three-speed planetary three-speed planetary gear changer can be expressed as

$$R_{r1} = -(1 - \xi_{32})/\xi_{32} = 1.6 \quad (4)$$

$$R_{r2} = 1 \quad (5)$$

$$R_{r3} = -\xi_{32}/(1 - \xi_{32}) = 0.6 \quad (6)$$

For the planetary gear speed changer, the requirement of reduction ratios is $R_{r1}/R_{r2} \geq R_{r2}/R_{r3}$. Based on (4)–(6), if $\xi_{32} = -1.6667$ then $R_{r1} = 1.60$, $R_{r2} = 1$, $R_{r3} = 0.60$, and $R_{r1}/R_{r2} = 1.6 = R_{r2}/R_{r3} = 1.6$. For the Planetary gear train shown in Fig. 10a, if $Z_2 = 45$, $Z_5 = 75$, and $Z_3 = 15$, then $\xi_{32} = -1.6667$. Figure 12 shows the corresponding three gear positions. Table 2 shows the clutch sequence of the corresponding three-speed planetary gear speed changer.

Figure 13a shows its corresponding three-speed automatic transmission including one planetary gear speed changer with $R_{r1} = 1.6, R_{r2} = 1$, and $R_{r3} = 0.6$ and the ordinary gear reducer with $R_{r(O)} = 10.91$. Hence, the three speeds of automatic transmission for electric motorcycle are 17.456, 10.92, and 6.546.
Table 2. Clutch sequence of invention 1.

<table>
<thead>
<tr>
<th>Speeds</th>
<th>C4</th>
<th>C5</th>
<th>Owc4</th>
<th>Owc5</th>
<th>Reduction Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>2nd</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3rd</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>0.6</td>
</tr>
</tbody>
</table>

(a) Three-speed transmission  (b) Four-speed transmission

Fig. 13. Automatic transmission for electric motorcycle.

Table 3. Clutch sequence of invention 3.

<table>
<thead>
<tr>
<th>Speeds</th>
<th>C4</th>
<th>C5</th>
<th>Owc4</th>
<th>Owc5</th>
<th>Reduction ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>1.615</td>
</tr>
<tr>
<td>2nd</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3rd</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>0.619</td>
</tr>
</tbody>
</table>

Invention 3. For a planetary gear train shown in Fig. 10c, its train value $\xi_{ji} > 1$. According to Eq. (1), the reduction rations of three-speed planetary gear transmission can be also expressed as Eqs. (4)–(6). Based on Eqs. (4)–(6), if $\xi_{32} = 2.587$ then $R_{r1} = 1.63$, $R_{r2} = 1$, $R_{r3} = 0.613$ and $R_{r1}/R_{r2} = 1.63 = R_{r2}/R_{r3} = 1.63$. For the planetary gear train shown in Fig. 14, if $Z_2 = 24$, $Z_5 = 63$, and $Z_{p1} = Z_{p2} = 15$, then $\xi_{32} = 2.625$, and $R_{r1} = 1.615$, $R_{r2} = 1$, $R_{r3} = 0.619$. Figure 14 shows the corresponding three gear positions. Table 3 shows the clutch sequence of the corresponding three-speed planetary gear changer.

6.2. Four-Speed Automatic Transmissions

Invention 4. For a three-speed automatic transmission for electric motorcycle to have the reduction ratios from 20 to 6.8 and the spacing of adjacent speed is constant. Table 4 shows the reduction ratio’s requirements
Table 4. Reduction ratio’s requirements of invention 4.

<table>
<thead>
<tr>
<th>Speeds</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction ratios</td>
<td>20</td>
<td>13.3</td>
<td>9.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Reduction ratios of planetary gear changer</td>
<td>2.1</td>
<td>1.4</td>
<td>1.0</td>
<td>0.716</td>
</tr>
<tr>
<td>Spacing of speeds</td>
<td>1.5</td>
<td>1.4</td>
<td>1.397</td>
<td></td>
</tr>
</tbody>
</table>

of this four-speed automatic transmission.

The four-speed automatic transmission consist one four-speed planetary gear speed changer and one ordinary gear reducer. According to Table 4, in this design, the reduction ratio of ordinary gear reducer is identified as $R_{\text{O}} = 9.5$. Hence the reduction ratios of four-speed planetary gear speed changer are 2.1, 1.4, 1 and 0.716. For a planetary gear speed changer shown in Fig. 11a, according to Eq. (1), the reduction ratios of this four-speed planetary gear transmission can be expressed as

$$R_{r1} = (\xi_{53} - \xi_{52})/(1 - \xi_{52})$$  \hspace{1cm} (7)

$$R_{r2} = \xi_{52}/(1 - \xi_{52})$$  \hspace{1cm} (8)

$$R_{r3} = 1$$  \hspace{1cm} (9)

$$R_{r4} = -(1 - \xi_{52})/\xi_{52}$$  \hspace{1cm} (10)

Based on Eqs. (7)–(10), if $\xi_{32} = -2$, $\xi_{52} = 3.5$, and $\xi_{53} = -1.75$ then $R_{r1} = 2.101$, $R_{r2} = 1.401$, $R_{r3} = 1$, and $R_{r4} = 0.714$. $R_{r1}/R_{r2} = 1.5 \geq R_{r2}/R_{r3} = 1.401 \geq R_{r3}/R_{r4} = 1.401$. For the planetary gear train shown in Fig. 11a, we have that if $Z_2 = 24$, $Z_3 = 48$, $Z_6 = Z_7 = 15$, and $Z_5 = 84$, then $\xi_{32} = -2$, $\xi_{52} = 3.5$, and $\xi_{53} = -1.75$. Figure 15 shows the corresponding four gear positions. Table 5 shows the clutch sequence of the corresponding four-speed planetary gear changer. Figure 13b shows its corresponding four-speed automatic transmission including one planetary gear speed changer with $R_{r1} = 2.1$, $R_{r2} = 1.4$, and $R_{r3} = 1$, and $R_{r4} = 0.714$ and the ordinary gear reducer with $R_{\text{O}} = 9.527$. Hence, the three speeds of automatic transmission for electric motorcycle are 20.01, 13.34, 9.527, and 6.8.

7. CONCLUSIONS

In this paper, we propose a design methodology for the invention of planetary gear type automatic transmissions for electric motorcycles. First, applying the check-list method (combining, changing, and transferring methods), the design concepts are proposed. Then, based on the design concepts proposed and train value equation of planetary gear train, we derive the reduction-ratio equations of planetary gear changers. Finally,
Table 5. Clutch sequence of invention 4.

<table>
<thead>
<tr>
<th>Speeds</th>
<th>C4</th>
<th>C4’</th>
<th>C5</th>
<th>Owc3</th>
<th>Owc4</th>
<th>Owc5</th>
<th>Reduction ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>2.1</td>
</tr>
<tr>
<td>2nd</td>
<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1.4</td>
</tr>
<tr>
<td>3rd</td>
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<td>*</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4th</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.714</td>
</tr>
</tbody>
</table>

Based on above reduction-ratio equations, the corresponding planetary gear changer can be synthesized. In this paper, five new design concepts including three 3-speed and two 4-speed are synthesized. Furthermore, three examples of the kinematic design of planetary gear type automatic transmissions are presented to illustrate the design methodology. Based on the proposed methodology, all planetary gear type automatic transmissions can be synthesized. The results of this paper will be valuable contributions to electric motorcycle engineering.

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**REFERENCES**


