Control Strategy and Function Design Based on Lever Analogy

Hua Tian and Peng Chen

Abstract Lever analogy is very useful in analyzing gear-train including more than one planetary gear sets. The lever analogy is a translational-system representation of the rotating parts for the planetary gear. Applying lever analogy to GM 6T40E transmission, kinematic and dynamic analysis is shown in this paper. Model based shift control strategy is based on dynamic lever analogy. By setting target output torque and desired turbine speed profile, the clutch pressure and torque request to engine can be commanded. With more investigation on lever analogy, enhanced control strategy and new function are already invented.

Keywords Lever analogy · Planetary gear · Steady state analysis · Dynamic analysis · Shift control strategy

1 Introduction

For AT, planetary gear-set is always a complicated mechanism to analysis. Even we can build the right equation from the basic math model, the analysis is not flexible especially with different connection mechanism or working condition. With lever analogy, the planetary mechanism can be simplified. Steady state analysis is the primary usage of this method. Besides that, the control strategy can be designed based on lever analogy too. And with deeper understanding on lever structure, new function can be invented.

F2012-C02-019

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SAE-China and FISITA (eds.), *Proceedings of the FISITA 2012 World Automotive Congress*, Lecture Notes in Electrical Engineering 193,
DOI: 10.1007/978-3-642-33744-4_16,

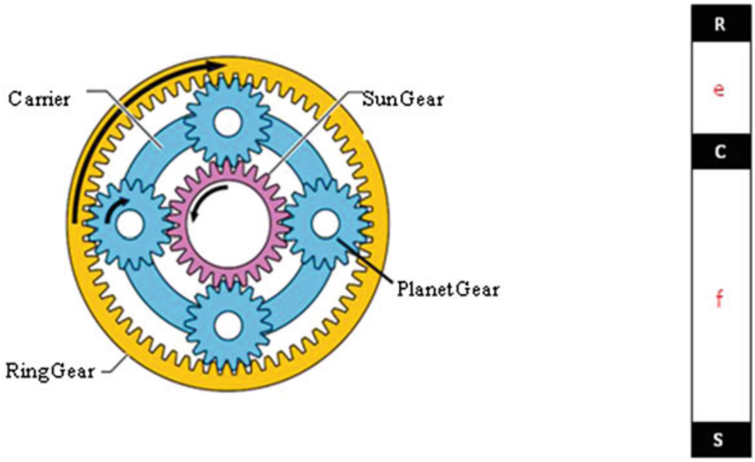


Fig. 1 Lever analogy of simple planetary gear set

2 Lever Analogy

Lever analogy is a translational-system representation of the rotating parts for the planetary gear. In the lever analogy, an entire simple or compound planetary gear train can be usually represented by a single vertical lever. The input, output and reaction torques are represented by horizontal forces on the lever. The lever motion, relative to the reaction point, represents rotational velocities.

A simple planetary gear set consists of sun gear, planet gear, ring gear and carrier. As shown in Fig. 1, it can be represented as a lever, which has 3 nodes. 3 nodes are sun gear (S), carrier (C), and ring gear (R). The distance between sun gear node and carrier node (f) represents the number of teeth on ring gear, and distance between ring gear node and carrier node (e) represents the number teeth on sun gear. The lever can be rescaled in the architecture with more than one simple planetary gear set.

With the lever, torques of rotating parts is analogous to force on nodes. Angular velocities of parts are analogous to linear velocities on nodes. Angular accelerations are analogous to linear accelerations on nodes. For each lever, it needs to be at balanced state with summary of force and torque to be zero.

3 Steady State Analysis

GM 6T40E is a six-speed clutch-to-clutch automatic transmission. It consists of 3 sets of simple planetary gear architecture [1]. Figure 2 shows the cross section. For multiple planetary gear sets, the lever can be rescaled based on some basic rules. The relative relationship between each node of one lever should not be changed

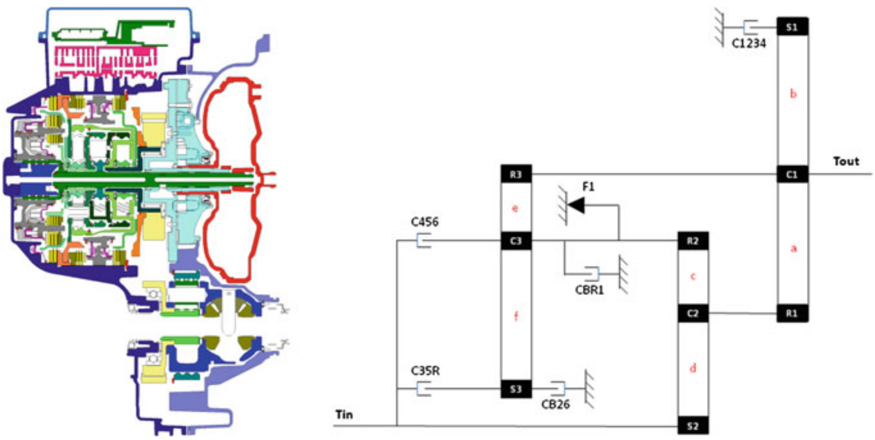


Fig. 2 Cross section and lever analogy of 6T40E

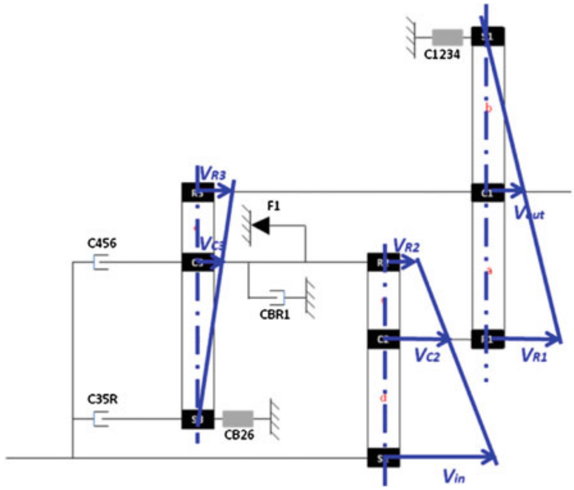


Fig. 3 Rotating speed analogy

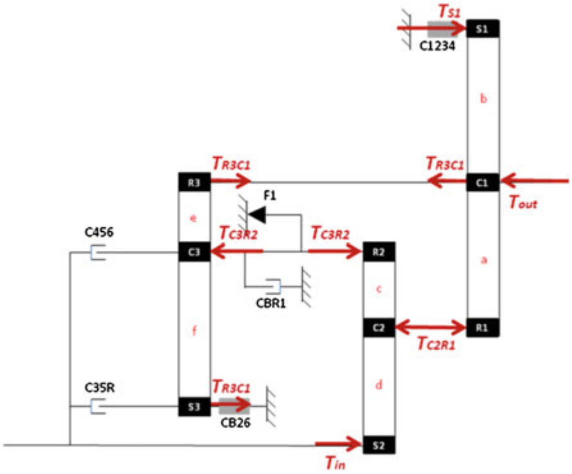
although the length can be rescaled. Also, the distance between same parts should be same at different lever. Based on these rules, the lever analogy is built as shown in Fig. 2.

Taking second gear as example, Figs. 3 and 4 show the kinematic and dynamic status for each node and lever. Figure 3 is used to calculate the rotating speed. Figure 4 is used to calculate torque.

Based on Fig. 3, equations can be built as below:

$$V_{out} = V_{R3}$$

Fig. 4 Torque analogy



$$V_{out}/V_{R1} = b/(a+b)$$

$$V_{C3}/V_{R3} = f/(e+f)$$

$$(V_{C2} - V_{R2})/(V_{in} - V_{R2}) = c/(c+d)$$

$$V_{C3} = V_{R2}$$

$$V_{C2} = V_{R1}$$

Then, gear ratio of second gear is calculated as:

$$\frac{V_{in}}{V_{out}} = \left(1 + \frac{d}{c}\right)\left(\frac{a+b}{b} - \frac{f}{e+f}\right) + \frac{f}{e+f} = 2.964$$

Based on Fig. 4, equations can be built as below:

$$(T_{out} + T_{R3C1}) \times b = T_{C2R1} \times (a+b)$$

$$T_{C2R1} \times c = T_{in} \times (c+d)$$

$$T_{R3C1} \times (e+f) = T_{C3R2} \times f$$

$$T_{C3R2} \times c = T_{in} \times d$$

Then, torque ratio of second gear is calculated as:

$$\frac{T_{out}}{T_{in}} = \frac{(a+b) \times \frac{c+d}{c} - \frac{d}{c} \times b \times \frac{f}{e+f}}{b} = 2.964$$

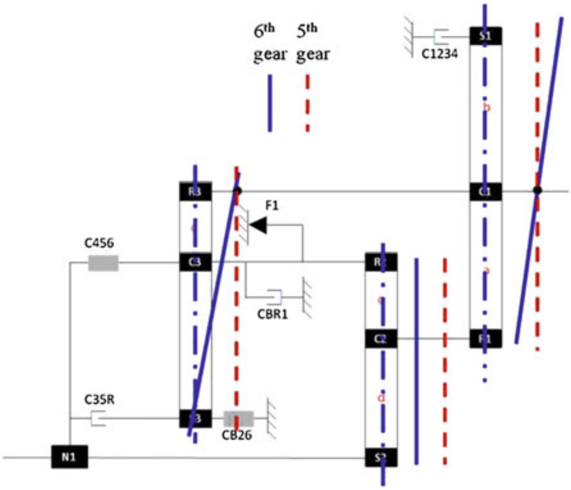


Fig. 5 Rotating speed analogy

4 Dynamic Analysis and Shift Control Strategy

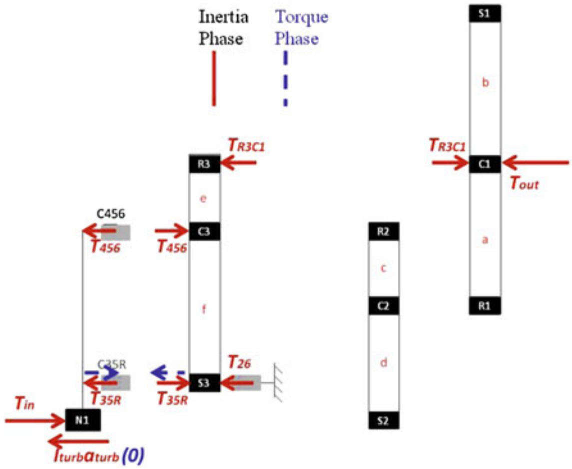
During shift, some clutches are controlled to have slip. The torque it carries is decided by the pressure on clutch plates, relative rotating speed, and the power flow status of whole system. At the same time, rotating speed makes inertia have impact on the shift process. So, dynamic analysis is more complicated. This paper will take power on downshift from 6th gear to 5th gear as example. Compared to other rotating parts, input shaft related inertia is much bigger. To simplify the calculation, only the input shaft related inertia is taken into consideration.

An idea shift process is separated into inertia phase and torque phase. During inertia phase, clutch is controlled to slip and achieve the target speed ratio. Torque transfer between different clutches is accomplished in torque phase. Figures 5 and 6 show the lever analogy during shift.

4.1 Inertia Phase

During inertia phase, one clutch named as offgoing clutch is controlled to slip. Turbine speed is increasing with the clutch slip. In this phase, inertia torque needs to be considered.

Fig. 6 Torque analogy



$$\sum F_1 = 0 \Rightarrow T_{R3C1} - T_{out} = 0 \Rightarrow T_{out} = T_{R3C1}$$

$$\sum M_{C3} = 0 \Rightarrow T_{R3C1} \times e - T_{26} \times f + T_{35R} \times f = 0 \Rightarrow T_{R3C1} = (T_{26} - T_{35R}) \times \frac{f}{e}$$

$$\sum M_{R3} = 0 \Rightarrow T_{456} \times e + (T_{35R} - T_{26}) \times (e + f) = 0 \Rightarrow T_{456} = (T_{26} - T_{35R}) \times \frac{e + f}{e}$$

$$\sum F_{N1} = 0 \Rightarrow T_{in} - I_{turb} \times a_{turb} - T_{456} - T_{35R} = 0 \Rightarrow a_{turb} = \frac{T_{in} - T_{456} - T_{35R}}{I_{turb}}$$

Then we have:

$$array*20l T_{out} = (T_{26} - T_{35R}) \times \frac{f}{e} \qquad a_{turb} = \frac{T_{in} - \frac{e+f}{e} \times T_{26} + \frac{f}{e} \times T_{35R}}{I_{turb}}$$

4.2 Torque Phase

When it goes into torque phase, clutch C35R changed the relative rotating speed. As a result, the direction of torque will change. In torque phase, the speed ratio of target gear has been achieved. Within the short time of shift, we can deem vehicle speed as constant. Equations are built as:

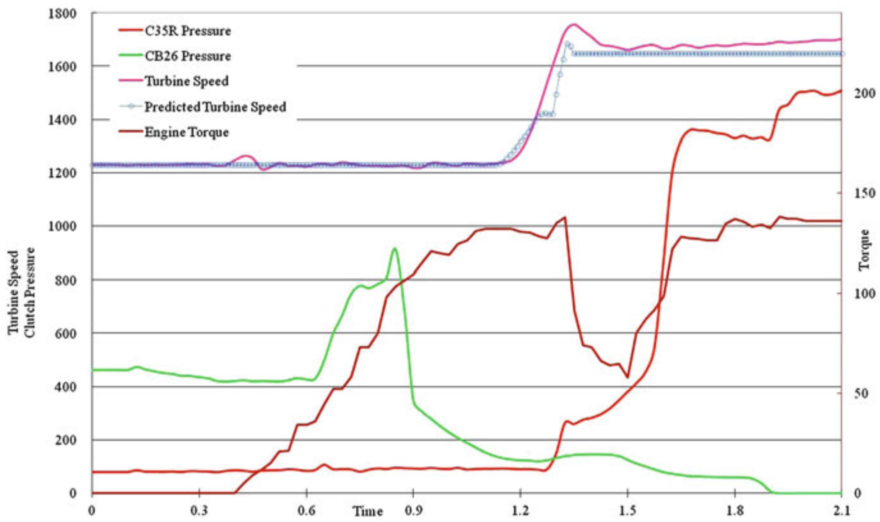


Fig. 7 Predicted turbine speed by lever analogy

$$\sum M_{R3} = 0 \Rightarrow T_{456} \times e - (T_{35R} + T_{26}) \times (e + f) = 0 \Rightarrow T_{456} = (T_{26} + T_{35R}) \times \frac{e+f}{e}$$
$$\sum F_{N1} = 0 \Rightarrow T_{in} - T_{456} + T_{35R} = 0 \Rightarrow T_{in} = T_{456} - T_{35R}$$
$$\sum F_1 = 0 \Rightarrow T_{R3C1} - T_{out} = 0 \Rightarrow T_{out} = T_{R3C1}$$
$$\sum F_3 = 0 \Rightarrow T_{456} - T_{35R} - T_{26} - T_{R3C1} = 0 \Rightarrow T_{456} = T_{35R} + T_{26} + T_{R3C1}$$

Then we can get:

$$T_{in} = \frac{e+f}{e} \times T_{26} + \frac{f}{e} \times T_{35R}$$
$$T_{out} = \frac{f}{e} \times T_{26} + \frac{f}{e} \times T_{35R}$$

Model based control strategy is based on those equations [2]. By setting the target output torque and desired turbine speed profile, the expected clutch torque and input torque can be calculated. Then clutch pressure and torque request to engine is commanded.

To check how accurate the model strategy is, we did some tests in the car. An imperfect shift is picked to be investigated. For this shift, the lever analogy would be more complicated because speed change is not finished by the end of inertia phase, which means inertia torque needs to be considered in torque phase. And the torque would change based on relative rotating speed. Using collected clutch real pressure and engine torque, turbine speed can be calculated by the lever analogy. Figure 7 shows the trace. We can see the flare exist in torque phase. And the predicted turbine speed by lever analogy model is very sensitive to show that.

5 Conclusion

Lever analogy is very useful for gear-train analysis especially more than one planetary gear sets. It is a good tool for analysis and design. As shown in this paper, it can be used for steady state and dynamic analysis. It is also used in control strategy design like model based control strategy in 6T40E. With more investigation with this method, an enhanced control strategy on power on downshift is developed by GM and started to be implemented. Based on the lever analogy, a hill-hold function is proposed by author and in the patent process.

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