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Study on shift schedule saving energy of automatic transmission of ground vehicles*

GONG Jie (龚 捷)[†1,2], ZHAO Ding-xuan (赵丁选)[1], CHEN Ying (陈 鹰)[2], CHEN Ning (陈 宁)[1]

([1]*College of Mechanical Science and Engineering, Jilin University, Changchun 130025, China*)

([2]*State Key Lab of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*)

[†]E-mail: gongjie@zju.edu.cn

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Abstract: To improve ground vehicle efficiency, shift schedule energy saving was proposed for the ground vehicle automatic transmission by studying the function of the torque converter and transmission in the vehicular drivetrain. The shift schedule can keep the torque converter working in the high efficiency range under all the working conditions except in the low efficiency range on the left when the transmission worked at the lowest shift, and in the low efficiency range on the right when the transmission worked at the highest shift. The shift quality key factors were analysed. The automatic transmission's bench-test adopting this shift schedule was made on the automatic transmission's test-bed. The experimental results showed that the shift schedule was correct and that the shift quality was controllable.

Key words: Ground vehicle, Hydrodynamic drive, Automatic transmission, Shift schedule, Saving energy, Shift quality
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INTRODUCTION

The technology of automatic transmission in the automobile is widely applied in the ground vehicle to increase productivity and decrease intensity of labor. However, the performance of the ground vehicle in various operating conditions, such as low speed, heavy load and sharply changing load, is very different from that of the automobile in normal operation. Therefore, the ground vehicle cannot adopt the method of the lock-up clutch used in the automobile to solve the problem of the torque converter working in its low efficiency range (Gong, 2002). In order to make reasonable use of energy sources, a shift schedule is studied in order to decide which shift could ensure that the torque converter works in its high efficiency range according to the actual load. This is the problem of shift's decision-making.

As we know, the engine and torque converter in the vehicle drivetrain are complicated nonlinear systems very difficult to control. The main advantage of fuzzy control incorporating human experiences in the algorithm is its ability to deal with nonlinear systems and not requiring a formal analytical structure in application. In the last decade, a number of researchers conducted exploratory work on fuzzy control for the control systems of the automatic transmission (Yamaguchi *et al*., 1993; Sakaguchi, 1993; Shen, 1997). Compared with the traditional control, fuzzy control is a satisfactory but not an optimal control. In this study, we are concerned with the control effect of the torque converter and transmission on the vehicular drivetrain and determining that the torque converter

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is maintained working in its high efficiency range by gear shift with a new shift schedule.

SHIFT SCHEDULE

Shift scheduling adjusts the shifting moment (of various shifts of the automatic transmission changes) with the control parameters. It is the key technology of the automatic transmission developed; and directly affects the vehicular economic and power performance.

This section is organized as follows: First, the definitions of high efficiency range and low efficiency range are given. Then, the reason why the torque converter works in the low efficiency range is discussed. Finally, the method for solving the problem is presented.

Definitions of high efficiency range and low efficiency range

In order to evaluate the economic performance of the torque converter, the efficiency of the torque converter is required to be no less than an ideal value $\eta_{tc\ min}$ in use ($\eta_{tc\ min}$=75% in engineering machinery, $\eta_{tc\ min}$=80% in the automobile usually). The primary characteristic of YJ355 torque converter is shown in Fig.1 (Zhao *et al.*, 2001). There are two points meeting the condition of $\eta_{tc}=\eta_{tc\ min}$. The whole working condition of the torque converter is divided into three regions by the two points, namely, the low efficiency range locating in low speed ratio, high efficiency range and low efficiency range locating in high-speed ratio. When the torque converter works in the low efficiency range while the working condition point locates in the low- or high-speed ratio, the shift schedule must control the transmission to shift so as to keep the torque converter working in the high efficiency range.

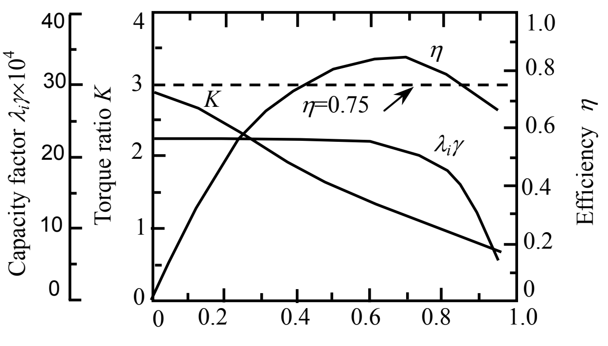

Fig.1 YJ355 Torque converter primary characteristics

Reason for the torque converter's working in low efficiency range

The torque converter can multiply the torque, according to various operating conditions. For the ground vehicle equipped with the torque converter, the working condition point of the torque converter is moved to the low efficiency range locating in the low speed ratio from the high efficiency range as the vehicle's sustaining resistance increases. Contrarily, the working condition point of the torque converter is moved to the low efficiency range locating in the high speed ratio from the high efficiency range as the vehicle's sustaining resistance decreases. It can be known that the auto-control systems can keep the torque converter working in the high efficiency range by limiting the range of the torque converter's torque variation. Consequently, a shift schedule formula is deduced as follows.

Shift theory

The shift schedule aims to control and set the common working point of engine and torque converter so that the torque converter efficiency η_{tc} is no less than the ideal value $\eta_{tc\ min}$; in other words, the points satisfying the condition $\eta_{tc}=\eta_{tc\ min}$ are used as the shift points. The gear shift is decided by the automatic transmission control system's calculated transmission gear ratio that controls the torque converter to work in the range $\eta_{tc}\geq\eta_{tc\ min}$.

The ground vehicle model is shown in Fig.2 (Gong and Zhao, 2001a; 2001b).

First, we consider the case of the torque conv-

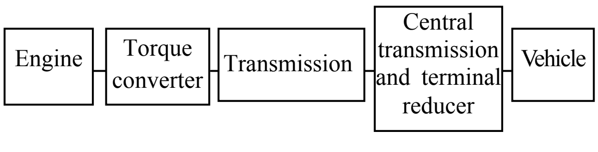

Fig.2 Model of vehicle

erter working in the low efficiency range locating in the low speed ratio. It is supposed that the two points in Fig.1 represent the working condition point in the low efficiency range locating in the low speed ratio and the shift point meeting the condition of $\eta_{tc} = \eta_{tc\ min}$, respectively, and T_{tc}, $T_{tc\ lim}$ represent the two points' torque, respectively.

Suppose that the transmission gear ratio is i_t. To move the working condition point to the high efficiency range from the low efficiency range, the transmission is used to increase the torque. Then there is

$$i_t = T_{tc} / T_{tc\ lim} \tag{1}$$

When the torque converter works in the low efficiency range locating in the high speed ratio, Eq.(1) is obtained in the same way, where the difference is that $T_{tc\ lim}$ is the output torque corresponding to the shift point in the high speed ratio.

The above two situations are considered together. Since the function of the transmission in the vehicular drive system is to adjust the output torque of the drive system by gear shift, the above obtained i_t is the multiple (or fraction) of the transmission output torque at the next moment. However, during a continuous shift, the transmission is already in a certain shift, that is, the transmission output torque has been magnified to a fraction at the present moment and the magnitude is the gear ratio of the transmission. Therefore, the multiple (or fraction) of the transmission output torque at the next moment must be increased (or decreased) by a factor i_t again. In other words, the gear ratio at the next moment must be increased (or decreased) by a factor i_t on the basis of the present gear ratio, that is

$$i_{t\ next} = i_{t\ present} i_t \tag{2}$$

where $i_{t\ next}$ is the transmission gear ratio at the next moment, $i_{t\ present}$ is the transmission gear ratio at present.

From Eqs.(1) and (2), the shift schedule formula is as follows:

$$i_{t\ next} = i_{t\ present} \frac{T_{tc}}{T_{tc\ lim}} \tag{3}$$

Although the ideal gear ratios of the transmission are continuous values, the actual gear ratios of the transmission supplied are discrete finite values. In practical applications, the gear ratio is chosen according to whether the working condition point of the torque converter locates in the low speed ratio region or in the high one. Under the condition that the working condition point of the torque converter locates in the low speed ratio region, the lowest shift is chosen when the calculated gear ratio is larger than the maximum gear ratio of the transmission. Otherwise the bigger gear ratio will be chosen when the calculated gear ratio is between the two actual gear ratios of the transmission. Under the condition that the working condition point of the torque converter locates in the high-speed ratio region, the highest shift is chosen when the calculated gear ratio is smaller than the minimum gear ratio of the transmission. Otherwise the smaller gear ratio will be chosen when the calculated gear ratio is between the two actual gear ratios of the transmission.

Now, an example is taken to show how it is used. Suppose that a transmission with 4 shifts, $i_4 < i_3 < i_2 < i_1$, where i_n is gear ratio, n is shift, and =1,2,3,4. The shift is chosen as shown in Table 1.

Method to prevent shift cycling

As discussed before, the upshift point and the downshift point are the same in the above shift schedule. In order to prevent the transmission "hunting" in use, a method is adopted to distinguish

Table 1 Shift choosing measure

	Shift when the working point is in low speed ratio	Shift when the working point is in high speed ratio
$i_{t\ next} < i_4$	–	4
$i_4 < i_{t\ next} < i_3$	3	4
$i_3 < i_{t\ next} < i_2$	2	3
$i_2 < i_{t\ next} < i_1$	1	2
$i_{t\ next} > i_1$	1	–

the normal from the frequent gear that changes shift.

Firstly, since the shift frequency of the ground vehicle is nearly a thousand times per hour (Wang *et al*., 2000), the minimum time interval from one shift to the next is chosen to be 2 seconds. Suppose that the time of the data acquisition is t (ms), the frequency of the shift decision between two shifts is $2000/t$. Therefore, when the frequency of the upshift (or downshift) is half of the shift decision times, it is a frequent gear changes shift. When the times of the upshift (or downshift) are the same as the shift decision times, it is a normal gear changes shift.

The method not only adapts to the above shift schedule, but also acts as a general method for all shift schedules to avoid shift cycling.

SHIFT QUALITY

The gear shift is completed by controlling clutch or brake to engage or disengage. As shift quality is closely linked to whether a shift schedule can be applied to the actual vehicle, it is necessary to discuss the deliberated index and the main factors affecting shift quality, in order to provide a theoretical basis for improving shift quality.

At present, jerk is used as the deliberated index of shift smoothness. Jerk is defined as the change of the longitudinal acceleration of the automobile. Its mathematical expression is (Lei *et al*., 1999)

$$j=\frac{\mathrm{d}\alpha}{\mathrm{d}t}=\frac{\mathrm{d}^2v}{\mathrm{d}t^2}=\frac{r_\mathrm{r}}{i_0}\frac{\mathrm{d}^2\omega_{0\mathrm{T}}}{\mathrm{d}t^2}=\frac{r_\mathrm{r}}{i_0I_\mathrm{W}}\cdot\frac{\mathrm{d}\left(T_{0\mathrm{T}}-T_\mathrm{W}\right)}{\mathrm{d}t}=\frac{r_\mathrm{r}}{i_0I_\mathrm{W}}\cdot\frac{\mathrm{d}T_{0\mathrm{T}}}{\mathrm{d}t} \quad (4)$$

where j, α, v are the jerk, acceleration and speed of the vehicle, respectively, t is time, r_r is the wheel radius, i_0 is the gear ratio between the transmission output shaft and the driving wheel, $w_{0\mathrm{T}}$, $T_{0\mathrm{T}}$ are the angular velocity and torque of the transmission output shaft, respectively, T_W is the resistance moment acting on the wheel, and supposed to be unchanged during a shift, I_W is the moment of inertia relating to the part of the transmission output shaft.

The above formula shows that the effective method of decreasing jerk is to control the effect of torque change on the transmission output shaft, that is, to make the torque change minimum.

BENCH-TEST

In order to verify the shift schedule, an automatic transmission test experiment was made on an automatic transmission's test-bed.

Component of automatic transmission's test-bed

The components and control method of the automatic transmission's test-bed is shown in Fig.3. It can be seen that the automatic transmission's test-bed consists of an engine, a torque converter, a transmission, a speed increaser, and an electric eddy current dynamometer. The engine is a power supply. The electric eddy current dynamometer is a power dissipation device used for loading for the drivetrain by adjusting winding current to change the brake load. The speed increaser is used for matching the rotational speed for the electric eddy current dynamometer. During the test, the speed and torque of the engine and the torque converter were acquired and processed by a computer. The computer control actuator's electromagnetic valve

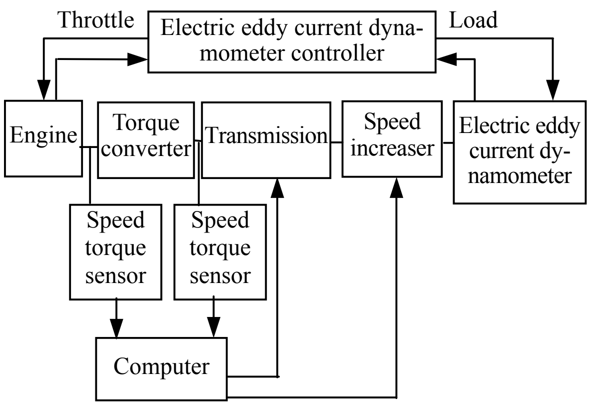

Fig.3 Schematic diagram for the automatic gear shift's test-bed

opened or closed to implement shift according to the shift schedule.

Experimental results of shift schedule

The torque converter efficiency was controlled to be over 75% in the test. The time interval of the data acquisition was set to be 200 ms. The experimental results obtained by connecting the points of the data acquisition are shown in Fig.4. The course of downshift corresponded with that of increasing load in Fig.4b. The course of upshift corresponded with that of decreasing load. The points of efficiency less than 75% in Fig.4a were those determined by shift decision. The experimental results proved that the shift schedule saving energy could make torque converter work in the high efficiency range by gear shift according to the actual load acting on the drivetrain.

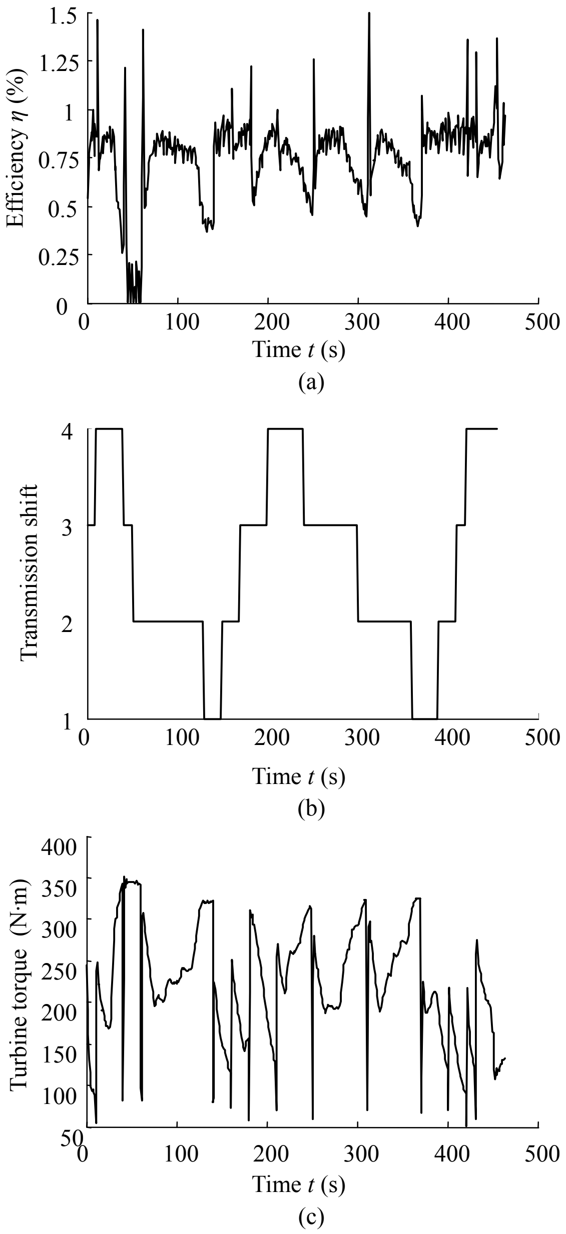

Fig.4 Experimental results of the automatic gear shift's test-bed (a) Efficiency change; (b) Transmission shift change; (c) Turbine torque change

Experimental results of shift quality

The measured results of the torque converter output torque are shown in Fig.4c.

1) On the test site, we felt that the impact and vibration of the downshift were stronger than that of the upshift. The reason for this, as explained by Eq.(4) and Fig.4c, is that the torque change of the downshift is bigger than that of the upshift.

2) There is a trough in Fig.4c, corresponding to each shift point. This phenomenon indicates occurrence of power interruptions during gear shift.

3) To study the controllability condition of shift quality, the thirteen shift points in the test were carefully analysed. To expound the course of gear shift, the experimental data of three gear shift courses were extracted from the experimental record, and listed in Table 2. In order to easily describe the course of the gear shift. The measured point, after shift instruction is sent out, is called a shift point and marked as point 1. The point before the shift point is marked as point 0. The point after the shift point is marked as point 2, the rest can be deduced by analogy. The torque converter output torque of each group has the following changing rule: the torque converter output torque of point 1 is less than that of point 0, the torque converter output torque of point 2 reduces more than that of point 1, the torque converter output torque of point 3 increases more than that of point 2, the torque converter output torque of point 4 is the biggest among those of point 2, point 3 and point 5.

The course of the gear shift indicates that the clutch of the original shift began to slip at point 1. The clutch of the original shift disengaged and the clutch of the new shift did not engage at point 2. At this moment, power interruptions occurred. The clutch of the new shift began to slip at point 3 and engaged at point 4.

Conclusion

From the above experimental results, we can conclude that:

1) The shift schedule saving energy can maintain the torque converter working in the range of an ideal value under all the working conditions except the following two cases, one is the low efficiency range on the left when the transmission works in the lowest shift, and the other is the low efficiency range on the right when the transmission works in the highest shift.

2) Random load was imposed on the drivetrain during the test. Although the above shift schedule saving energy was obtained by the studying torque converter's primary characteristic, the experimental results showed that the shift schedule saving energy is correct while the torque converter is working under conditions of the kinetic characteristic.

3) In order to reduce the impact of the gear shift in the test, it could be known that the clutch of the new shift should be engaged 200 ms earlier than that of the original shift to be disengaged. Therefore, shift quality can be improved by timing control.

Table 2 Experimental data of three shift courses

Group	Point	Shift	Torque converter output torque (N·m)
1	0	4	315.374
	1	3	313.302
	2	3	58.9293
	3	3	221.085
	4	3	280.663
	5	3	256.832
2	0	3	323.145
	1	2	322.627
	2	2	78.0979
	3	2	290.507
	4	2	296.723
	5	2	272.374
3	0	2	324.699
	1	1	323.663
	2	1	66.1823
	3	1	108.664
	4	1	223.676
	5	1	212.278

SUMMARY

In order to solve the problem of the low torque converter efficiency in the automatic transmission of the ground vehicle under heavy load, a new shift schedule saving energy is proposed for the automatic transmission of the ground vehicle. Experiment on the automatic transmission bench-test adopting this shift schedule was made on the automatic transmission's test-bed. The experimental results showed that the shift schedule was correct and that shift quality was controllable. The above research results provide reliable basis for application to ground vehicle and improving shift quality.

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