Application of external air temperature estimation to a variable lubrication control system for a new 9-speed automatic transmission for rear-wheel-drive vehicles

Yuki TAWARA*　Yoshihisa KODAMA*　Masahiro YAMAMOTO*

Summary

The new 9-speed automatic transmission for use on rear-wheel-drive vehicles is fitted with a system that enables independent control of the lubricant flow rate. Ascertaining the temperature of the oil flowing in the lubrication circuit is essential in order to optimize the lubricant flow rate to match the driving situation. That requires an estimation of the oil temperature drop in the air-cooled oil cooler. To do that, an engine intake air temperature sensor is used to estimate the external air temperature for determining the oil temperature drop in the oil cooler, which enables variable lubrication control.

1. Introduction

Automatic transmission fluid (ATF) serves various purposes and one of its key functions is lubrication. The existing 7-speed unit is not able to regulate the lubricant flow rate independently, which could become excessive depending on the driving situation, resulting in increased friction.

The new 9-speed automatic transmission (9AT) for rear-wheel-drive vehicles can control the lubricant flow rate independently to reduce friction. The lubricant flow rate is greatly affected by the pressure loss due to the oil temperature drop that occurs in the air-cooled oil cooler. That makes it necessary to control the flow rate by taking into account the magnitude of the oil temperature drop. For the new 9AT, a method of controlling the lubricant flow rate was developed that monitors the magnitude of the oil temperature drop in the air-cooled oil cooler based on an estimation of the external air temperature.

2. Targeted system

The configuration of the lubrication system circuit that was the focus of this study is explained first. As shown in Fig. 1, after the ATF pressure is regulated by the control valve, the oil flows to the torque converter and then to the built-in oil cooler (BIOC). In the BIOC, heat exchange takes place between the ATF and the engine coolant. The BIOC

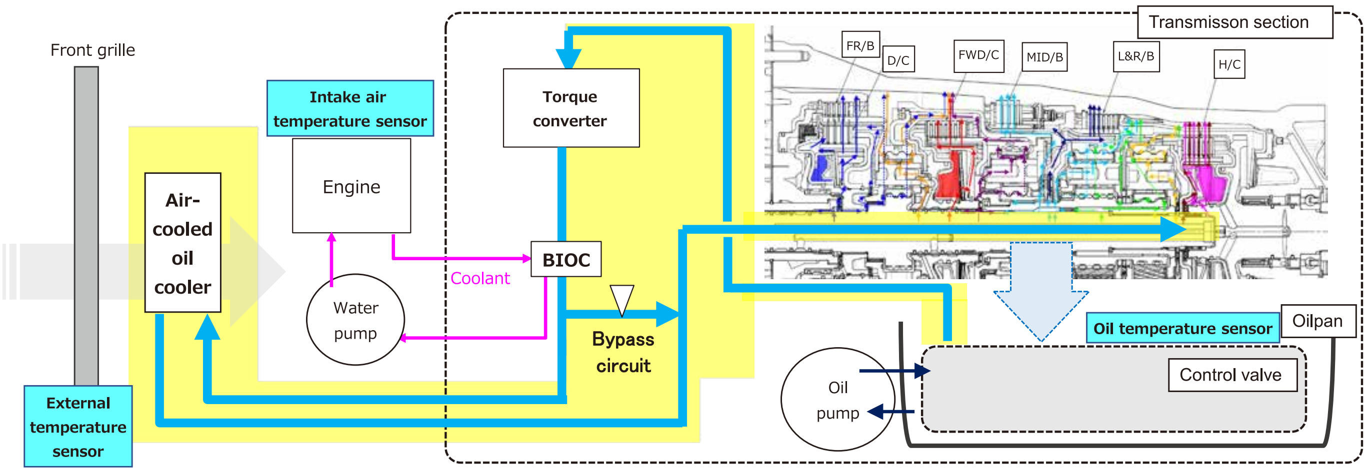

Fig. 1 Cooling and lubrication circuit

* Hardware System Development Department

functions as a warmer to warm the ATF when the inlet oil temperature is low and as a cooler to cool the ATF when inlet oil temperature becomes high.

A bypass circuit is provided right after the BIOC. A wax serves to open and close the bypass circuit by using the characteristic that its volume changes according to the temperature. The bypass circuit is open when the temperature of the oil flowing through it is low, and the ATF follows a return circuit back to the transmission without passing through the air-cooled oil cooler. The bypass circuit is closed when the oil temperature is high, so the ATF flows into the air-cooled oil cooler. The ATF is cooled there by the heat exchange that occurs with the external air flowing through the air-cooled oil cooler. The new 9AT is expected to be used on large vehicles such as pickup trucks for the U.S. market, so an air-cooled oil cooler with high cooling performance is necessary.

As shown in Fig. 2, the source pressure for supplying lubricant (i.e., lubricant pressure) is created by a lubricant linear solenoid valve, which is activated by a control signal from the controller, and by a lubricant regulator activated by the output pressure of the solenoid valve. A larger lubricant flow rate is needed to protect and cool the transmission

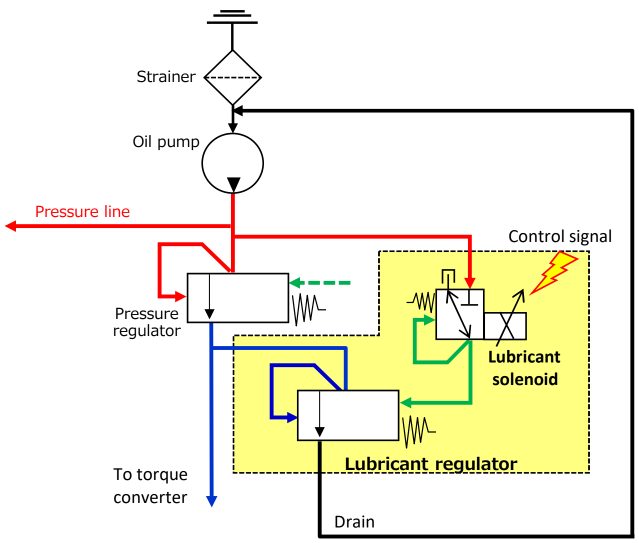

Fig. 2 Lubrication system in control valve

parts in high load driving situations where the transmitted torque and rotational speed are high, but a smaller flow rate is sufficient under low loads. Accordingly, a variable lubrication control system was built for the new 9AT that optimizes the lubricant flow rate by regulating the lubricant pressure according to the driving load.

3. Issues in targeted system

As explained in the preceding section, when the temperature of the ATF flowing through the bypass circuit is low, the bypass circuit is open so the oil does not pass through the air-cooled oil cooler; when the ATF temperature rises, the bypass circuit is closed so the oil begins to flow to the air-cooled oil cooler.

Figure 3 shows the lubrication circuit and the change in the oil temperature after the ATF becomes hot and the bypass circuit is closed. The red line shows the condition where the BIOC functions as a cooler under a high external air temperature. The blue line shows the condition where the BIOC functions as a warmer under a low external air temperature. Because the ATF is heated in the BIOC under this condition, the bypass circuit is closed and the ATF flows to the air-cooled oil cooler.

The magnitude of the oil temperature drop in the air-cooled oil cooler is greatly influenced by the temperature

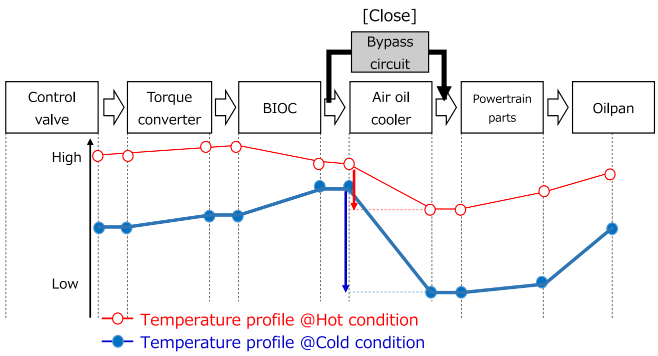

Fig. 3 Oil temperature fluctuation in lubrication circuit

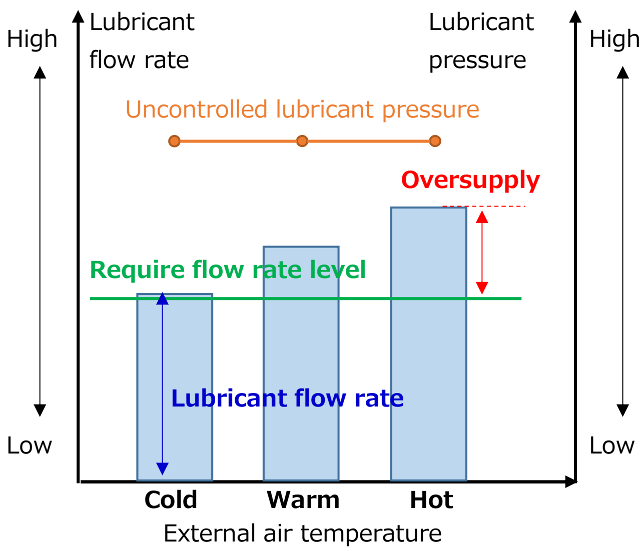

Fig. 4 Uncontrolled lubricant flow rate

Table 1 Decision analysis results

	Installation of new sensor	Diversion of existing sensor to estimate oil temp. at air-cooled oil cooler outlet	
	Proposal (1)	Proposal (2)	Proposal (3)
	Air-cooled oil cooler outlet oil temp. sensor	External air temp. sensor	Engine intake air temp. sensor
Accuracy	○	○	△
Difficulty of control	△	×	△
Sensor installation rate	×	△	○
Judgment	No GO	No GO	**GO**

of the external air flowing through the cooler. The oil temperature drop is larger with a low external air temperature than with a high external air temperature. That tendency is especially pronounced with a large-capacity air-cooled oil cooler.

In short, it was initially thought that only the driving load needed to be considered in the variable lubrication control system. However, it was found that the effects of the magnitude of the oil temperature drop in the air-cooled oil cooler and the resultant pressure loss also have to be considered. If the lubricant pressure is aligned with a low external air temperature condition where a large pressure loss occurs, the lubricant flow rate will become excessive under a high external temperature condition. Accordingly, this kind of situation must also be eliminated (Fig. 4).

4. Development of a solution

Using an estimated external air temperature value would make it possible to ascertain the magnitude of the oil temperature drop in the air-cooled oil cooler and also the resultant pressure loss. Reflecting the results in variable lubricant flow rate control would provide a countermeasure for the issues mentioned above.

4.1 Estimation of external air temperature using engine intake air temperature

The magnitude of the oil temperature drop in the air-cooled oil cooler must be reflected in the variable lubrication control procedure in order to optimize the lubricant flow rate. The oil temperature at the inlet of the air-cooled oil cooler is estimated from the operating temperature of the bypass circuit. Several proposed methods were investigated for estimating the oil temperature at the outlet of the air-cooled oil cooler.

Proposal (1) involved newly installing a temperature sensor to measure the outlet oil temperature directly. Proposals (2) and (3) involved estimating the oil temperature at the air-cooled oil cooler outlet indirectly based on the temperature of the external air passing through the cooler. Table 1 presents the results of a decision analysis (DA) that was conducted from the following perspectives: "accuracy" of calculating the outlet oil temperature, "relative difficulty of constructing a control system" using a sensor, and the "sensor installation rate" on vehicles for applying the system to all relevant vehicles.

The results revealed it would be difficult to adopt proposal (1) from the standpoint of the "sensor installation rate" and proposal (2) from the standpoint of the "relative difficulty of constructing the control system". It was decided to proceed with proposal (3) involving the use of the engine intake air temperature sensor to estimate the external air temperature and then using the result to calculate the oil temperature at the outlet of the air-cooled oil cooler. With respect to accuracy, it will be noted that there are driving situations where the engine intake air temperature and the external air temperature diverge. That divergence has been minimized by adding a temperature correction procedure to the control system.

4.2 Relationship between oil temperature drop in the air-cooled oil cooler and pressure loss

The method of estimating the external air temperature was selected. However, in order to estimate the oil temperature at the outlet of the air-cooled oil cooler, it was necessary to estimate the effects of the external air temperature and oil flow rate in the cooler on the magnitude of the oil temperature drop and the resultant pressure loss. It will be noted that with the bypass circuit closed, the oil flow rate in the oil cooler and the lubricant flow rate are equal. The selected method involves two steps: (1) to estimate the oil temperature drop in the air-cooled oil cooler due to the external air temperature; (2) to estimate the values of the pressure loss in the air-cooled oil cooler and in the following downstream section relative to the oil temperature drop in the oil cooler. They are explained in detail below.

First, the heat exchange characteristic in the air-cooled oil cooler is used to explain the relationship between the oil flow rate in the oil cooler and the oil temperature drop. The heat exchange characteristic E [kW] is defined by the following parameters.

• Oil temperature at air-cooled oil cooler inlet T_{IN} [°C]
• Oil flow rate in air-cooled oil cooler Q_{OIL} [L/min]
• Temperature of air flowing through air-cooled oil cooler = external air temperature T_{AIR} [°C]
• Air velocity in air-cooled oil cooler V_{AIR} [m/s]

The oil temperature at the air-cooled oil cooler outlet T_{OUT} [°C] has the following relationship with the oil temperature drop ΔT_{OIL} [°C] in the oil cooler.

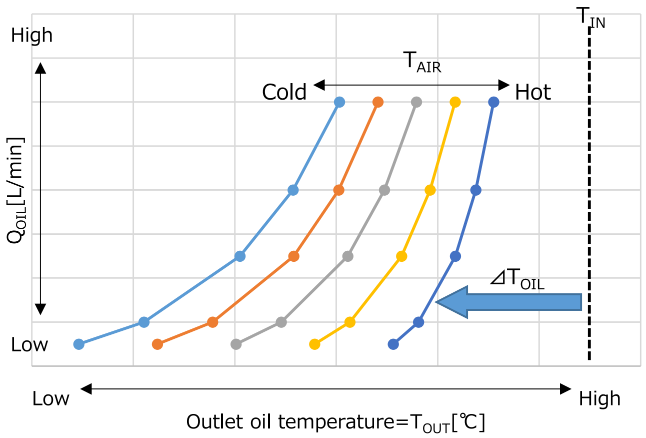

Fig. 5 Estimated oil temperature drop

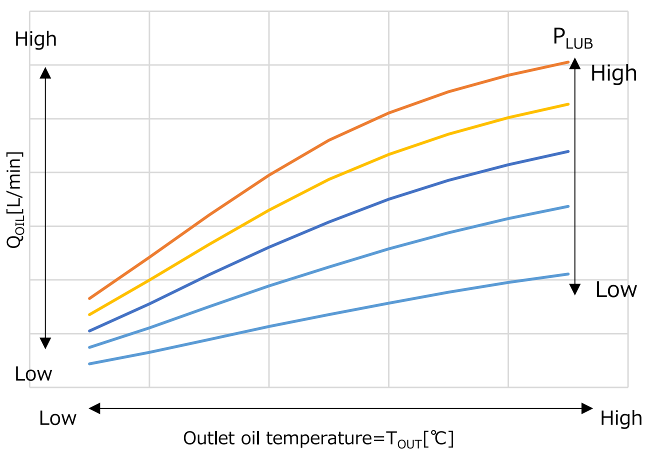

Fig. 6 Estimated oil flow resistance

$$T_{OUT} = T_{IN} - \Delta T_{OIL} \tag{1}$$

Letting η [kJ/kg K] represent the specific heat of the oil, ΔT_{OIL} can be expressed with the following equation.

$$\Delta T_{OIL} = \frac{\mathrm{E}(T_{IN},\ \mathrm{Q_{OIL}},\ T_{AIR},\ \mathrm{V_{AIR}})}{\eta \times Q_{OIL}} \tag{2}$$

From Eqs. (1) and (2), the oil temperature at the air-cooled oil cooler outlet T_{OUT} can be expressed as shown below.

$$T_{OUT} = T_{IN} - \frac{\mathrm{E}(T_{IN},\ \mathrm{Q_{OIL}},\ T_{AIR},\ \mathrm{V_{AIR}})}{\eta \times Q_{OIL}} \tag{3}$$

Figure 5 shows the oil temperatures that were calculated at the outlet of the air-cooled oil cooler based on Eq. (3). The horizontal axis is the oil temperature at the oil cooler outlet T_{OUT} and the vertical axis is the oil flow rate in the oil cooler Q_{OIL}. These temperatures were calculated under a condition of the lowest oil temperature at the inlet of the air-cooled oil cooler T_{IN} and with the bypass circuit closed. The air velocity in the air-cooled oil cooler V_{AIR} was calculated assuming a high driving speed. The blue arrow in the figure indicates the oil temperature drop ΔT_{OIL} in the air-cooled oil cooler. It is seen that the oil temperature at the oil cooler outlet T_{OUT} decreases with a smaller oil flow rate in the oil cooler Q_{OIL} and when the external air temperature is low.

Next, the relationship between the lubricant pressure and the lubricant flow rate is explained based on the pressure loss characteristic in the air-cooled oil cooler. The lubricant flow rate Q_{OIL} can be expressed in relation to the lubricant pressure P_{LUB} as shown in the equation below.

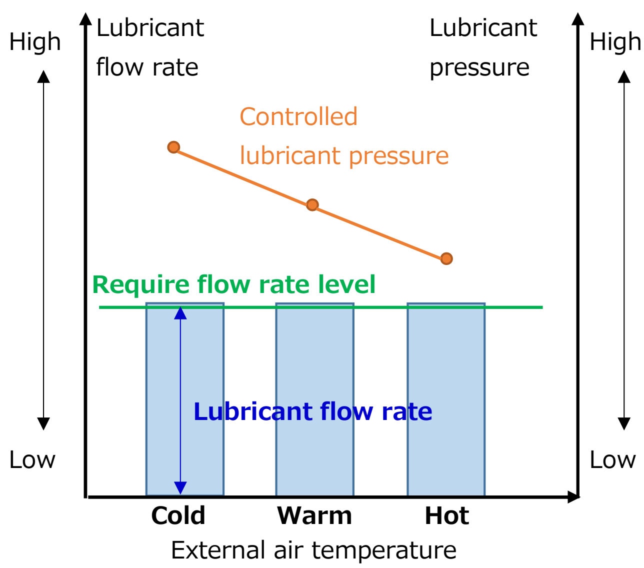

Fig. 7 Controlled lubricant flow rate

$$Q_{OIL} = R_1(T_{IN}, T_{OUT})P_{LUB} + R_2(T_{IN}, T_{OUT})\sqrt{P_{LUB}} \quad (4)$$

where R_1 and R_2 are coefficients of oil flow resistance in the lubrication circuit and are sensitive to T_{IN} and T_{OUT}.

As was done in the case of Fig. 5, by setting T_{IN} constantly at the oil temperature for closing the bypass circuit, Q_{OIL} becomes a function of T_{OUT} and P_{LUB}. The calculated results for Q_{OIL} are shown in Fig. 6 on the same axis as in Fig. 5. It is seen that the pressure loss in the lubrication circuit increases when T_{OUT} is low, so the lubricant flow rate decreases at the same lubricant pressure.

As is clear by looking at Eqs. (3) and (4), Q_{OIL} and T_{OUT} calculated with these equations, respectively, are parameters of the other equations, which means that each one cannot be calculated independently. It is necessary to find a solution as a set of Q_{OIL} and T_{OUT} that satisfies both equations. In this project, a solution under each set of conditions was found by numerical calculation and mapped. The necessary lubricant pressure was then derived by calculating back from the desired lubricant flow rate.

4.3 Attainment of variable lubrication control by estimating the external air temperature

As a result of the development work described above, a variable lubrication control system was built based on the estimated value of the external air temperature. This system provides variable control of the lubricant flow rate that takes into account the oil temperature drop in the air-cooled oil cooler and the resultant increased pressure loss.

The effects of the system are shown in Fig. 7. The lubricant pressure is regulated according to the estimated value of the external air temperature. This enables the necessary lubricant flow rate to be optimally supplied regardless of the external air temperature. Consequently, it is now possible to prevent an excessive lubricant flow rate even in environments with a high external air temperature.

5. Conclusion

- A variable lubrication control system was built based on the estimated value of the external air temperature. The system optimally controls the lubricant flow rate by taking into account the oil temperature drop that occurs in the air-cooled oil cooler depending on differences in the external air temperature. It thus achieves both durability and lower friction.
- An engine intake air temperature sensor is used in estimating the external air temperature. The use of this highly versatile, existing device will enable the new 9AT transmission to be applied to a wide range of vehicle models in the future.

■ Authors ■



Yuki TAWARA　Yoshihisa KODAMA　Masahiro YAMAMOTO