Development of High Efficiency Dog Clutch with One-Way Mechanism for Stepped Automatic Transmissions

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ABSTRACT: In order to reduce drag losses and a clutch actuator load, the new dog clutch system for stepped automatic transmission is developed. Transmitting torque is converted to the engaging force because rotating shaft and dog clutch are connected with the helix spline. The drag losses of this clutch are reduced by 50 to 60%, and the clutch actuator load is reduced by 50% compared to conventional multi-plate wet-type clutch.

KEY WORDS: power transmission, automatic transmission, mechanism / Clutch, Efficiency, Longitudinal acceleration [A2]

1. Introduction

Multi-plate wet-type clutches, which have high controllability of transmitting torque and can absorb torque-gap during gear shifting, are often applied to an automatic transmission (AT) and other automotive transmissions. However, they have loss factor in both engagement and overrun. During engagement, a hydraulic pressure of at least 1 MPa is generally necessary and is maintained with an oil pump. During overrun, oil drag losses occur between the friction plate and the separator. A gear train schematic of stepped AT is shown in Fig. 1(1). For a 1st-gear clutch, an one-way clutch (OWC) is provided in combination with a multi-plate wet-type clutch (B2) to reduce the torque-gap that occurs in the gear shifting from 1st to 2nd gear (1-2 gear upshift) (1)(2). The B2 is engaged when reverse running and the OWC is engaged when 1st gear running. The OWC transmits the 1st gear torque and passively disengages in concert with the engagement of the 2nd-gear clutch (B1). The torque-gap can thereby be reduced to less than that of the B2 to B1 upshifting. However, the OWC has approximately same drag losses the B2. Reducing the loss of the oil pump and the drag losses of the B2 and OWC are important to improve the transmission efficiency.

In recent years, the torque-gap in the B2 to B1 upshifting has been reduced by improving the shift control technology, and ATs without the OWC have been commercialized(3)(4). However, ATs without the OWC have oil pump losses during B2 engagement. While ATs which are replaced B2 with dog clutch also have been commercialized, torque-gap during gear shifting occurs(5). In the present study, a new clutch based on the dog clutch is proposed. The proposed clutch is shown in Fig. 2. The driving power is transmitted by the meshing of the dog clutch; it can reduce the piston force during engagement more than the B2 and therefore reduce the loss of the oil pump in supplying pressure to the piston. Because the area of sliding surfaces in overrunning is smaller than with the B2, the drag losses can be reduced.

Moreover, prototype of AT which are replaced B2 with the proposed clutch as the 1st gear clutch. If 1-2 gear upshift is performed, then the torque-gap can be reduced more than with the
conventional dog clutch for the reasons described in Section 2.2. From clutch unit tests, the loss-reducing effect was confirmed. In addition, vehicle running tests, the variation of longitudinal acceleration (the G-gap) generated by the torque-gap in 1-2 gear upshifting was validated.

2. High Efficiency Clutch

2.1. Function and structure

The proposed clutch links with the rotating shaft and the housing to stop the shaft rotation. The rotating shaft is in positive rotation with the dog rotor in a disengaged position. In negative rotation, it is in an engaged position. Therefore, these positions are changed passively in concert with the rotational direction of the rotating shaft. However, the engaged position is maintained by the piston in a reverse running. The four main components are as follows.

1. Dog stator with straight splines on internal surface, directly fixed to housing
2. Rotational shaft with helix splines on external surface, directly fixed to any elements of planetary gear set
3. Dog rotor with straight splines on external surface and helix splines on internal surface
4. Piston for maintenance of clutch engaging state

2.2. Characteristics

Fig. 2 shows the clutch in the disengaging state. The rotating shaft and the dog rotor are constantly engaged through the helix splines. The dog rotor arbitrarily translates when pushed by the piston and engages with the straight splines of the dog stator.

In a 1st gear running (with the dog rotor in the engaging state) with the power-on as shown on the left in Fig. 3. The rotating shaft rotates in the negative direction. The rotating force between the rotating shaft and the dog rotor is converted to an engaging force by the helix splines. It is therefore unnecessary to maintain the engaged position of the dog rotor using the piston.

In a reverse running, the rotational direction of the rotating shaft is inverted and the piston receives the disengaging force. While Piston needs to maintain the engaged position, the piston force of the proposed clutch is lower than that of the B2.

Clearance between the dog stator and the dog rotor is maintained in a 2nd gear running (with the dog rotor in a disengaging state), as shown in Fig. 2. The drag losses are therefore lower than that with the B2 with the sliding of multiple friction plates.

For 1-2 gear upshift, as shown on the right in Fig. 3, the piston is disengaged in advance. In a conventional dog clutch, the dog rotor is disengaged with piston disengagement. The driving force is therefore intercepted and torque-gap occurs. On the other hand, the dog rotor of the proposed clutch maintains the engaged position and the driving force is not intercepted during power-on. Next, the rotational direction of the rotating shaft is inverted by the B1 engagement. The dog rotor is passively disengaged as in the OWC. The torque-gap during gear shift is thereby reduced, and the G-gap is also reduced.

The dog rotor should be engaged by the torque of the rotating shaft without the piston force. Frictional resistance force in the translational direction occurs on the contact surfaces of the helix splines and straight splines. The lower limit of the helix angle of the helix spline is calculated by Eq. (1) so that the engaging force converted by the helix spline is higher than the frictional resistance force. If the helix angle is greater than the value obtained by Eq. (1), the dog rotor will not be stopped by the frictional resistance force during engagement. The helix angle also affects the disengaging force on the dog rotor in a reverse running. Therefore, the upper limit of the helix angle is set so that the disengaging force is less than the maximum piston force.

\[
\theta \geq \tan^{-1}\left\{\frac{D_{hs}}{D_{ss}} \cos \alpha \cdot \mu\right\} \quad \cdots (1)
\]

\[\begin{align*}
\theta & : \text{Helix angle of helix spline [deg]} \\
D_{hs} & : \text{P.C.D. of helix spline [mm]} \\
D_{ss} & : \text{P.C.D. of straight spline [mm]} \\
\alpha & : \text{Pressure angle of helix spline [deg]} \\
\mu & : \text{Friction coefficient}
\end{align*}\]

3. Test Methods

3.1. Clutch unit test

The rotating shaft torque of the B2 and the proposed clutch when disengaging were measured to compare the drag torque. The main cause of drag torque is the shearing force of the AT fluid between the sliding surfaces. The parameters were the rotational speed of the rotating shaft and the fluid conditions. The test conditions are shown in Table 1.

| Test condition | Rotational speed of rotating shaft [min⁻¹] | Oil temperature [°C] | Lubricant quantity [L/min] |
|---------------|------------------------------------------|----------------------|--------------------------|
|               | 1000, 2000                               | 30, 40, 80           | 2, 3                     |

Fig. 3 Behavior of proposed dog clutch

Table 1  Test condition

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3.2. Vehicle running test

The proposed clutch was replaced with the B2 and OWC in a conventional 6-speed AT. The structure of the prototype is shown in Fig. 4. The dog rotor was maintained in the disengaged position by return springs. Premature engagement caused by the external forces was prevented by these springs.

In the prototypes, a hydraulic system was also used by the conventional 6-speed AT. The piston area was changed to reduce the piston force without changing the piston pressure. When maximum engine torque was transmitted to the rotating shaft in a reverse run, the disengaging force on the dog rotor reached its maximum. The piston area that could maintain a piston force greater than the disengaging force was obtained by Eq. (2). As a result, the piston area of the proposed clutch was 50% lower than that of the B2 and the required piston force on the proposed clutch was also reduced by 50%.

Fig. 4 Proposed dog clutch in AT unit

\[ A_p = \frac{2T_e}{\cos \theta} \frac{\tan \theta - \mu \cos \theta}{P_o} + F_{rp} \]  \hspace{1cm} (2)

- \( A_p \): Piston area [mm²]
- \( T_e \): Max. revers engine torque [N•m]
- \( F_{rp} \): Load of return spring [N]
- \( P_o \): Hydraulic Pressure of oil pomp [MPa]

Table 2 Specification of test vehicle

| Parameter                  | Value          |
|----------------------------|----------------|
| Type of engine             | 2Litter, turbo |
| Max. engine power          | 175kW          |
| Max. engine torque         | 350Nm          |
| Total reduction ratio      | 13.7 (1st) 7.9 (2nd) |
| Tire diameter              | 0.358m         |
| Vehicle weight             | 1820kg         |

The prototype AT was installed in the test vehicle of the specification shown in Table 2. In the vehicle running test, the basic operation, including the premature disengagement by piston force insufficiency, are confirmed. Moreover, 1-2 gear upshifting is also performed and the G-gap is measured.

3.3. In-situ measurement

With the proposed clutch installed in the AT, the engaging and disengaging states can be estimated from the ratio of the AT input and output shaft rotational speeds. However, insufficient engaging cannot be discerned.

Fig. 5 Displacement sensor for dog rotor

Fig. 6 Measurement of dog rotor stroke

Fig. 7 Combination of clutch and micro data logger system
The translational position of the dog rotor is detected to confirm the clutch operation in the vehicle running test. The measurement object as a dog rotor translates on the rotating shaft, and it has splines on its external diameter. Because of the difficulty of measurement with a sensor mounted on the casing, a noncontact displacement sensor is mounted on the external diameter of the rotating shaft as shown in Fig. 5.

As shown in Fig. 6, a slope as a detected surface was formed in the translational direction on some of the internal splines of the dog rotor. The distance between the sensor and the detected surface changed with the translation of the dog rotor. Using the change in the sensor impedance, the amount of dog rotor translational distance was measured. In these measurements, it was necessary to record the signal of the sensor on the rotating shaft in the limited space of the AT unit. For that purpose, the ultra-small sized data logger system shown in Fig. 7 was developed. This system included the data logger, amplifier, and battery (6), (7). Its memory capacity was 32 to 64 MB and its sampling frequency was 10 to 100 kHz.

4. Test Results

4.1. Drag torque

In the 6-speed AT for these tests, the engine rotational speed in 4th and higher gears was equal to that of the rotating shaft. The drag torque is measured at up to 2,000 min⁻¹, the engine rotational speed range very frequently used in running vehicles. The measurement results are shown in Fig. 8.

In the B2, with its 5 friction plates, the area of the sliding surface in an overrunning is larger than the proposed clutch and the shearing force of the AT fluid is also higher. At a rotational speed of 1,000 min⁻¹, the results showed 50 to 60% lower drag torque with the proposed clutch than with the B2. At a rotational speed of 2,000 min⁻¹, the proposed clutch also had lower drag torque. The AT fluid intervening on the B2 sliding surface was expelled by centrifugal force. On the other hand, the proposed clutch no AT fluid expulsion effect of the centrifugal force. Therefore, the torque reduction ratio fell below 30%.

4.2. Longitudinal acceleration

The vehicle running tests (1-2 gear upshifting) were performed with the 3 ATs described in Table 3 installed in the vehicles. The AT#1 prototype used the conventional dog clutch. It was presumed that a large torque-gap would occur in 1-2 gear upshifting, and therefore running tests for the AT#1 and AT#2 prototypes under an engine torque of 150 N·m were performed. In 1-2 gear upshifting, the torque-gap occurs as a G-gap. Fig. 9 shows the measured G-gaps in the vehicle running tests.

In the prototype AT#1 with the conventional dog clutch, the 1st gear piston disengaged and the dog clutch also disengaged. If the dog clutch disengaged when the B1 transmittable torque was less than the engine torque, it entered neutral and engine overrun occurred. The B1 transmittable torque therefore became equivalent to the engine torque and it was desirable to match the timing of 0 N·m load torque in the dog clutch with the timing of dog clutch disengagement. It was difficult to match the timing of dog clutch disengagement, because of variation in the piston disengaging speed with the temperature of the piston hydraulic oil and because of measurement error in the B1 transmittable torque. In this test, the B1 transmittable torque was increased above the engine torque, after that the dog clutch was disengaged under the condition of the overlapping with the dog clutch torque and B1 torque.

Table 3  Clutch type of ATs

|               | 1st clutch | 2nd clutch |
|---------------|------------|------------|
| Conventional AT | Wet clutch(B2) & OWC | Wet clutch (B1) |
| Prototype AT #1 | Dog clutch |            |
| Prototype AT #2 | Proposed clutch |          |

As a result, the G-gap occurred in the direction of the vehicle acceleration. In the prototype AT#2 with the proposed clutch, if in
a power-on state, the dog rotor received the engaging force from the helix spline without piston force. In addition, the dog rotor was able to maintain its engaged position. Also, as described in Section 2.2, the dog rotor was disengaged in concert with the B1 engagement. The transmitting torque of proposed clutch did not overlap the B1 transmitting torque in a gear shifting. The G-gap as a result of 1-2 gear upshifting was less than half that of the conventional dog clutch.

4.3. Premature disengagement of dog rotor

As shown in Fig. 4, the dog rotor of the proposed clutch constantly receives disengaging force from the return springs. In the tests to present, an engine torque of more than 150 N·m was sufficiently high during 1-2 gear shifting. In addition, the engaging force received by the dog rotor exceeded the disengaging force from the return spring. Premature disengagement of the dog rotor occurred when the engine torque was low and a rate of increase of hydraulic pressure of the piston for B1 was slow in 1-2 gear upshifting. Therefore, the translational positions of the dog rotor and torque ratio were measured to confirm the state of the dog rotor, using the in-situ measurement system described in Section 3.3.

The torque ratio represents the ratio of the B1 transmittable torque to the engine torque. At a torque ratio of 0%, the proposed clutch for 1st gear transmits 100% of the engine torque. If the pressure of the 2nd gear piston is increased, the torque ratio also increases, and when it reaches 100%, complete shift to 2nd gear. Fig. 11 shows the results for 1-2 gear upshifting with an engine torque of 75 N·m and an increase rate of the torque ratio at 5%/sec. With an increase of the torque ratio, the engaging force on the dog rotor decreased. Also, the dog rotor received the disengaging force by the return springs. Therefore, the dog rotor gradually disengaged. When the dog rotor completed disengagement, a neutral state was entered temporarily without the torque ratio reaching 100%. It was inferred that premature disengagement of the dog rotor occurred and the rotational speed of the engine was quickly increased for that reason.

Next, Fig. 12 shows the result of 1-2 gear upshift with an increase rate of the torque ratio at 15%/sec. The torque ratio was approximately 80% until 1 sec before dog rotor disengagement, and the dog rotor was maintained engaging state. When the torque ratio reached 100%, the dog rotor completely disengaged and the shift to 2nd gear was performed without occurrence of premature disengagement of the dog rotor.

The premature disengagement can be counteracted even in 1-2 gear upshifting with low engine torque by optimization of an increase rate of the torque ratio.
5. Conclusion

A new clutch for automotive transmissions to reduce both the losses of the oil pump during engagement and drag losses during overrun was proposed. When this clutch was applied as the AT 1st clutch, although the basic structure of the proposed clutch is similar to the conventional dog clutch, it enables 1-2 gear upshifting without the torque-gap. In clutch unit tests, its drag losses reduction effect was confirmed. In vehicle running tests, the occurrence of a G-gap due to torque-gap in 1-2 gear upshifting was assessed, with the following results.

1. The multi-plate wet-type clutch which is used in a conventional AT, transmits the engine torque using friction, and requires a high piston force for that purpose. In contrast, the proposed clutch with its helix splines requires a piston force only in torque transmission during power-off and reverse running. Therefore, the proposed clutch can reduce the piston force by 50%.

2. The drag losses of the B2 and the proposed clutch during disengagement were measured for comparison. The torque was 50% to 60% lower with the proposed clutch than with the B2 under the condition of rotational speed of 1000min⁻¹.

3. The B1 transmitting torque did not overlap with the proposed clutch transmitting torque in 1-2 gear upshifting. This is because the proposed clutch was passively disengaged in concert with the B1 engagement. Therefore, the G-gap of the proposed clutch was less than half of that with the conventional dog clutch.

4. Premature disengagement of the dog rotor occurred when the engine torque was low and an increase rate of hydraulic pressure of the piston for B1 was slow in 1-2 upshifting. The timing of the dog rotor disengagement was confirmed with an in-situ measurement system. The premature disengagement can be counteracted even in 1-2 gear upshifting with low engine torque by optimization of an increase rate of the torque ratio.

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