

Clarification of parameters and development of a method for estimating loading forces acting on the spool valve of a hydraulically controlled automotive transmission

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Summary

The control valve used in hydraulically controlled automotive transmissions contains a spool valve that drains the excess portion of the fluid flow rate while regulating the pressure. The complex flow around the spool valve exerts various loading forces on the valve. These forces can delay valve response owing to increased sliding resistance and also press the valve against the control valve body, giving rise to concern about valve body wear. Although the forces acting on the valve can be calculated by fluid simulations, it has not been known whether the simulation results are correct. Therefore, in this study a load cell was used to measure the loading forces directly. The results confirmed that the tendencies of the calculated results obtained by fluid simulations agreed well with those of the experimental data, thereby verifying the validity of the simulation results.

1. Introduction

An automotive transmission uses a control valve to supply fluid to multiple hydraulic circuits and to regulate the pressure. Located inside the control valve is a spool valve that drains the excess portion of the fluid flow rate while adjusting the pressure. Loading forces induced by the fluid flow act on the spool valve during the draining process and exert various effects on the valve.

However, heretofore it has been difficult to measure the loading forces acting on the spool valve, although they have been calculated by fluid simulations. Consequently,

it has not been known whether the simulation results have been correct. For that reason, judgments about the feasibility of changing transmission specifications have to be based on experimental evaluations of response, wear and other performance parameters. Because specification changes require judgments based on experimentation, a lot of trial and error is involved, which can affect the product development period.

In this work, an experimental setup was built that can directly measure the loading forces acting on the spool valve. This paper presents the results measured with this setup, which confirm the validity of fluid simulations.

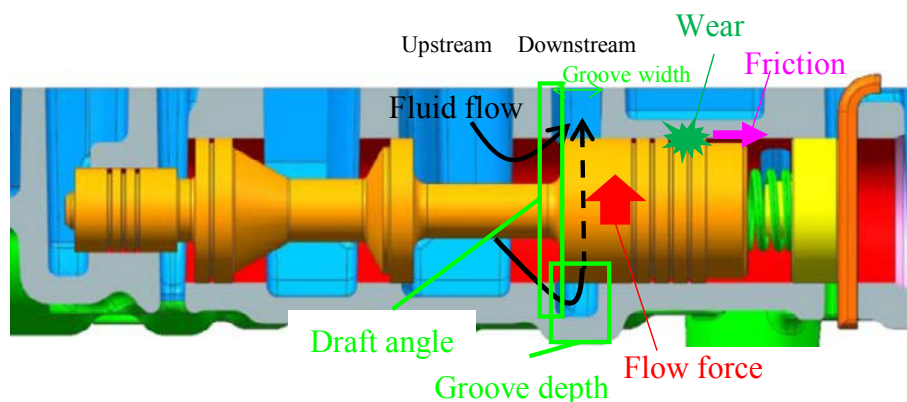


Fig. 1 Loading forces acting on the spool valve and their effects

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2. Spool valve structure and confirmation of dimensional effects

Figure 1 shows the structure of the spool valve for which experimental measurements were made in this study. As fluid flows from upstream to downstream, the loading forces produced by the fluid act on the valve to increase friction. That can cause a delay in responsiveness, which is a key characteristic for transmission control. In addition, the loading forces press the spool valve against the control valve body in which it is housed, giving rise to concern about valve body wear.

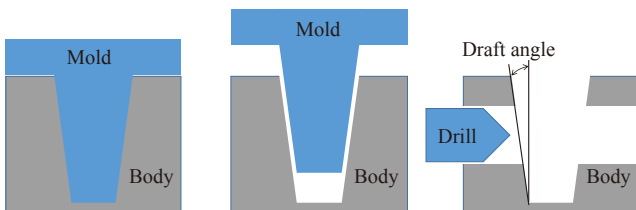


Fig. 2 Definition of draft angle

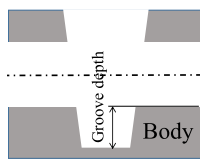


Fig. 3 Definition of groove depth

The experiments measured the effects of two dimensions, the draft angle and the groove depth. It was inferred from fluid simulation results that these two dimensions affect the loading forces.

The draft angle refers to the angle of inclination of the valve body wall and is defined as shown in Fig. 2. This inclination is provided to enable easy removal of the mold in the casting process, and the angle is retained by the valve body. The groove depth is defined as shown in Fig. 3.

3. Experimental setup

It would be difficult to directly measure the loading force that the spool valve inside the control valve applies to the latter valve body. However, the experimental setup was designed so that the force applied by the spool valve can be measured by a load cell via a rod used as a probe. The position of the rod was determined from simulation results and by confirming the point from wear marks where the spool valve pressed against an actual valve body. A hole was then drilled at that position for installing the rod.

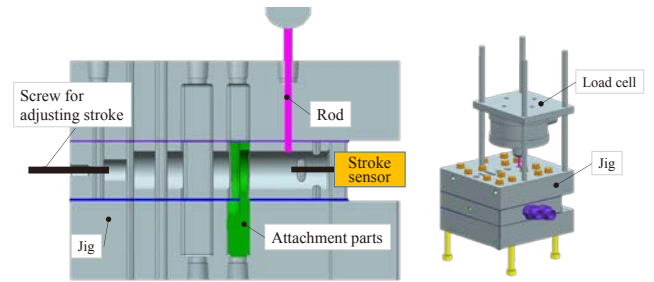


Fig. 4 Structure of jig, attachment parts and rod

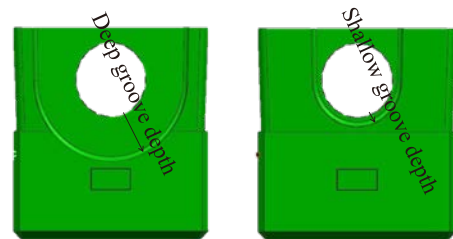


Fig. 5 Attachment parts

The rod passed through a jig to come in contact with the load cell installed above. This structure made it possible to measure the loading forces acting on the spool valve using the load cell via the rod.

The structure of the experimental setup is shown in Fig. 4. The shape of the area around the spool valve in an actual control valve was cut out in the jig, and the attachment parts shown in Fig. 5 enabled the dimensions around the spool valve to be varied. This setup made it possible to determine how the loading forces were affected by the dimensions around the spool valve.

In addition, a screw was provided in the jig at the end of the spool valve for adjusting the amount of stroke from outside the jig so that the pressure would apply force to the rod at the proper stroke position during the experiment.

Figure 6 shows the measured output of the load cell, representing the loading force applied to it when the upstream pressure was varied using the experimental setup described here. The specifications used in the experiment were a draft angle of 2.0 deg. and a groove depth of 11.5 mm. The vertical axes show the pressure and the loading force applied to the load cell in relation to time on the horizontal axis. The red line is the upstream pressure and the black line is the loading force.

The measured results show that the loading force rose along with the increase in the upstream pressure, indicating that the loading force followed the change in pressure. Presumably, this means that the flow rate increased owing to the differential pressure between upstream and downstream, thereby increasing the loading force

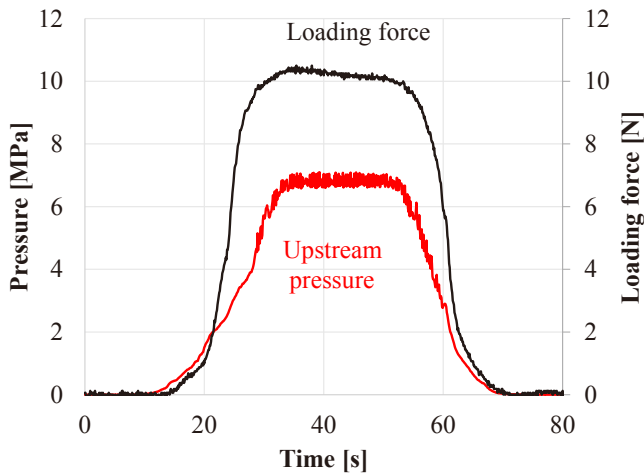


Fig. 6 Output of load cell related pressure

produced by the fluid flow. These results confirmed that the experimental setup was capable of measuring the loading force.

4. Simulation model

A 3D model was created of the jig, attachment parts and spool valve described above and used to conduct a fluid simulation of the loading force that was produced by the hydrodynamic force and acted on the position of the rod.

An example of the simulation model is shown in Fig. 7. The loading force simulated in this study acts in the annular clearance between the spool valve and the control valve body as illustrated in Fig. 8. Accordingly, computational accuracy was improved by modeling the annular clearance with a finer mesh.

The simulation conditions were aligned with those of the experiment. In both cases, the upstream pressure was 5.7 MPa, the downstream pressure was 0.7 MPa, the fluid temperature was 50 °C, and the specification of the spool valve diameter was 17 mm.

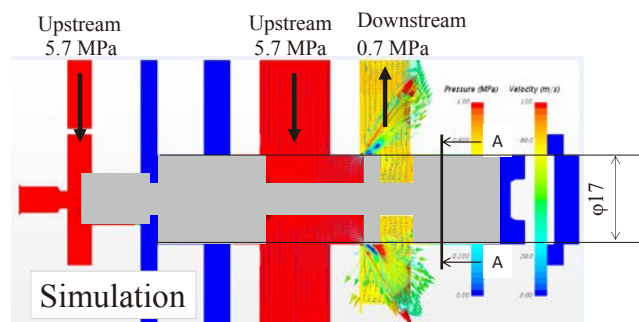


Fig. 7 Simulation model

Clearance:
Space between spool and body

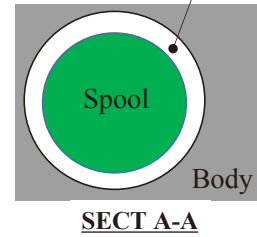


Fig. 8 Definition of clearance

5. Comparison of experimental and simulation results

The results obtained for the effect of the draft angle are shown in Fig. 9. The graph plots the loading force on the vertical axis as a function of the draft angle on the horizontal axis. The blue line is the experimental result and the red line is the simulation result. A loading force of 6.3 N was measured under a condition of a draft angle of 0 deg. It is seen that the loading force increased with a larger draft angle, and a value of 19.3 N was measured at an angle of 2.0 deg. The results of the fluid simulation conducted under the same conditions show a loading force of 14.8 N under a condition of a draft angle of 0 deg. and a value of 24.6 N at an angle of 2.0 deg.

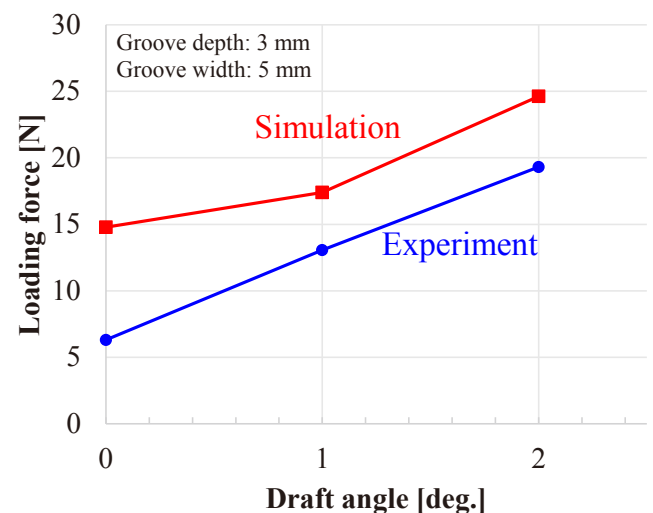


Fig. 9 Loading force as a function of draft angle

Although there is some discrepancy in absolute values between the experimental and simulation results, both sets of data show the same tendencies and effects on the loading force, thus confirming the validity of the simulation.

It is assumed that the reason for the effect of the draft angle on the loading force is that it produces a pressure unbalance between the circuit side and the back side, thereby applying force to the circuit side.

As the draft angle increases, a difference occurs in the size of the valve opening between the circuit side and the back side, with the opening becoming larger on the circuit side (Fig. 10). As a result, because the flow rate on the circuit side increases, the flow velocity becomes faster than on the back side. The pressure on the circuit side thus decreases, resulting in a differential pressure. The pressure around the spool valve on the circuit side declines locally to produce the pressure unbalance shown in Fig. 11.

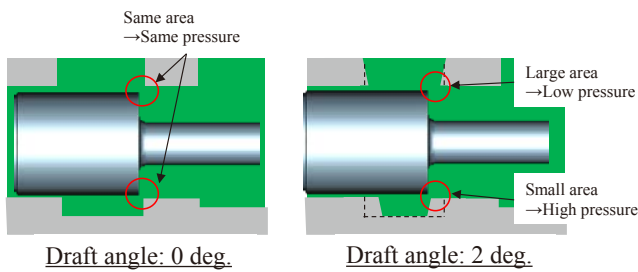


Fig. 10 Effect of draft angle

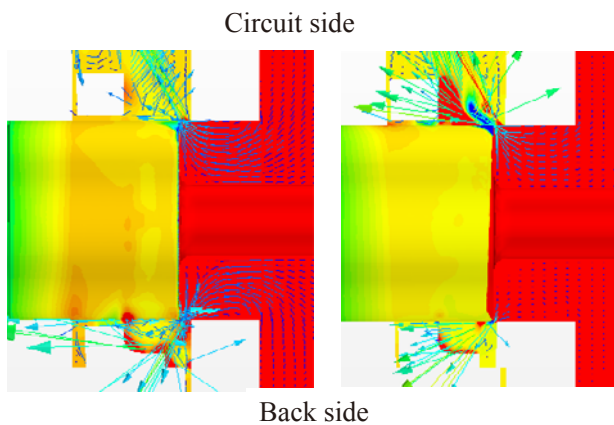


Fig. 11 Simulation results for draft angle

Figure 12 shows the results obtained for the effect of the groove depth. The loading force is plotted on the vertical axis as a function of the groove depth on the horizontal axis. The blue line is the experimental result and the red line is the simulation result. A loading force of 11.2 N was measured at a groove depth of 3.0 mm. The loading force decreased as the groove depth was increased, declining to 3.3 N at a groove depth of 11.5 mm. The simulation results show a loading force of 9.1 N at a groove depth of 3.0 mm

and a value of 3.8 N at a groove depth of 11.5 mm.

Although there is some discrepancy between the experimental and simulation results, both sets of data show the same tendencies, as was seen for the draft angle.

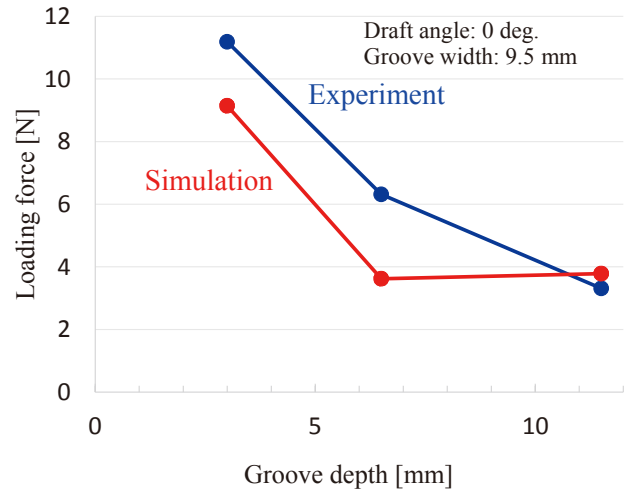


Fig. 12 Loading force as a function of groove depth

The action of the following two factors can be considered to explain the reason for the effect of the groove depth on the loading force.

- (1) The pressure rise induced by the collision of the fluid with the spool valve applies force to the circuit side.
- (2) The pressure gradient between the back side and the circuit side raises the pressure on the back side, thereby applying pressure to the circuit side.

As shown in Fig. 13, the first factor concerning the collision of the fluid with the spool valve occurs as the fluid in the grooves on the back side flows toward the circuit side (Fig. 14). In the case of a deep groove depth, the flow spreads out before the collision occurs so the effect of the collision is smaller. In contrast, in the case of a shallow groove depth, the effect of the collision is larger so a pressure rise is observed.

As shown in Fig. 15, the second factor concerning the pressure gradient occurs in the direction of the flow of the fluid between the spool valve and the valve body when the fluid in the grooves on the back side flows toward the circuit side. This is more pronounced for a shallow groove depth because the flow passage is narrower. The influence is small in the case of a deep groove depth (Fig. 16). As a result, the pressure on the back side rises compared with that on the circuit side, thus increasing the loading force.

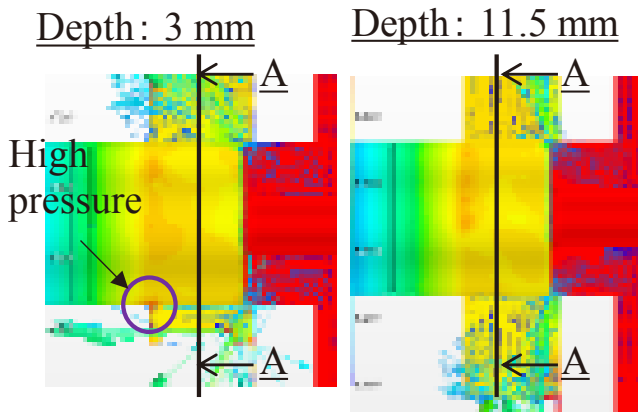


Fig. 13 Simulation results for groove depth

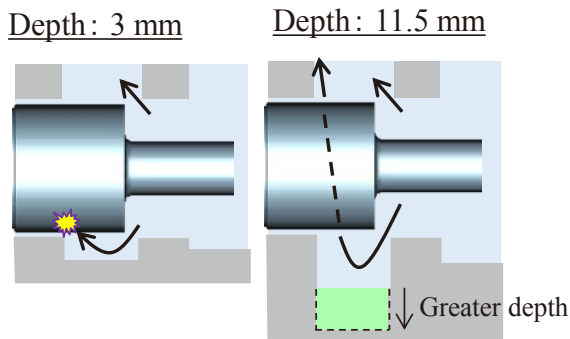


Fig. 14 Effect of groove depth

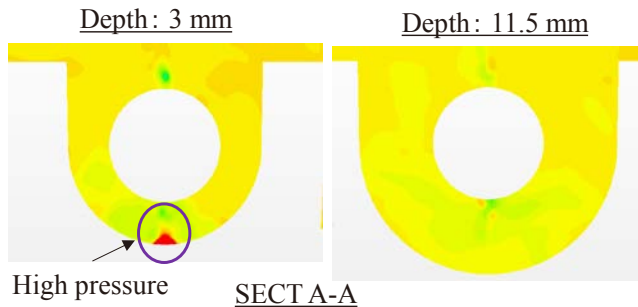


Fig. 15 Simulation results for groove depth in sect A-A

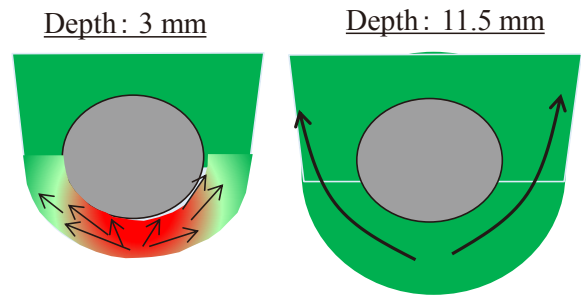


Fig. 16 Effect of pressure drop

6. Conclusion

- (1) Using a jig cut out in the shape of the area around the spool valve, a rod as a probe and a load cell, the loading forces acting on the valve were measured directly, which has been difficult to do heretofore.
- (2) A comparison of the experimental and simulation results revealed that there was some discrepancy in the absolute values, but both sets of data agreed well regarding the tendencies of the dimensional effects on the loading forces. This confirmed the validity of the simulation results.
- (3) This has now made it possible to make design judgments of transmission specifications at the development stage before conducting physical tests.

7. References

- This paper was presented at the 11th JFPS International Conference in October 2021.
- (1) Kenji Sakakibara, "Development of a hydraulic control system for a new JATCO wide-range CVT," 10th International CTI Symposium USA. Automotive Transmissions, HEV and EV Drives, USA, 2016, B2_Sakakibara_Jatco_paper, pp. 5-6.
 - (2) Masaru Shimada, "Application of CFD to develop a control valve spool featuring reduced fluid force," 2017 JSAE Congress (Autumn), No. 20176045

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