Development of Clutch System for Formula One Vehicle

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ABSTRACT

A direct push clutch (DPC) was developed to enhance the controllability of clutch torque in a Formula One clutch system. A direct push mechanism in which clamp force was generated by a plate with the function as lever and a hydraulic actuator was employed in place of the previous mechanism, in which the clamp force was generated by a diaphragm spring. The transition from stroke control to direct control of the clamp force did away with elements that formerly produced changes in system characteristics, such as variations in the diaphragm spring characteristic and spring hysteresis, and thermal expansion throughout the system. In combination with other enhanced control technologies, this enabled the development targets for the system to be realized. This helped to enable half-clutch starts (slip starts) to be employed from 2006, even after regulations prohibited the use of feedback control. As a result, a maximum reduction in time from 0-100 km/h of 0.46 sec (corresponding to a distance of approximately 11 m) was obtained, giving the vehicle a competitive advantage. The developed system was used in races from the first race of the 2006 season.

1. Introduction

One of the important functions demanded from the clutch systems used in Formula One vehicles is the control of torque at the start of the race in order to maximize tire performance. In 2003, feedback control using the tire slip rate as a parameter was commonly used to control clutch torque, enabling optimal clutch torque to be realized. However, changes to the Formula One regulations in 2004 prohibited the use of feedback control, necessitating the development of a clutch system in which clutch torque could be predicted with a high degree of accuracy.

The friction coefficient, μ, of the clutch friction material and the clamp force acting on the clutch friction material (clamp load) are factors that affect the accuracy of prediction of clutch torque. Of these, the clamp force can be controlled in a clutch system.

The conventional Formula One clutch system was termed “pull clutch” due to its mode of operation, and it originated in the clutches used in mass-production manual transmissions. A diaphragm spring was used to apply a clamp load to the dry carbon clutch friction material. A hydraulic actuator controlled the stroke in the direction that would detach the diaphragm spring, and clutch torque was controlled with the stroke as a parameter. Factors including variations in the dimensions of the component parts, variations in the diaphragm spring characteristics and spring hysteresis, and thermal expansion of the parts would cause the clamp load to change, making it challenging to accurately control clutch torque. As a result, slip start, a start method necessitating accurate clutch torque prediction, could not be used. A race start method known as dump start was employed to enable these issues to be avoided. This start method is used in conjunction with engine over-speed control, in which the clutch is instantaneously engaged and the tires are intentionally made to slip. However, when the tires are made to slip, their coefficient of friction, μ, temporarily declines, and ideal acceleration is not obtained. Development therefore commenced on a configuration that would do away with unstable elements and employ a direct clamp load control method, applying the clamp load directly by means of hydraulic pressure.

In 2004, Honda worked in collaboration with ZF SACHS Race Engineering GmbH (“SRE” below) to develop a dry multi-plate direct push clutch (DPC) provided with a lever disk plate with a return load that helped to ensure zero torque operation and a lever function that amplified the clamp load on the clutch friction material. A twin-piston clutch actuator in which hysteresis was reduced by lowering friction was simultaneously developed. These developments enhanced

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the accuracy of clamp load control, and helped to enable slip start to be employed. The reliability of the developed system was confirmed in vehicle tests in 2005, and it was employed on the track from the first race of the 2006 season. This helped to enable the achievement of a maximum reduction of 0.46 sec, corresponding to a distance of approximately 11 m, when accelerating from 0-100 km/h at race start.

2. Development Aims

The mechanism of production of clutch torque is simple, and can be expressed by the following equation:

$$Tc = FN \cdot \mu \cdot rm \cdot i \quad (1)$$

Tc: Clutch torque
FN: Clamp load
μ: Friction coefficient
rm: Effective radius of friction material
i: Number of disk surfaces

The controllability of the clamp load and the stability of the friction coefficient, μ, are therefore important factors in the accurate prediction of clutch torque.

In the conventional pull clutch configuration, the clamp load was generated as the reaction force to compression of the diaphragm spring by the clutch cover (Fig. 1).

The clamp load therefore varied with variations in the characteristics of the diaphragm spring and spring hysteresis, and with variations in the dimensions of the component parts and thermal expansion of the parts, making accurate control a challenge.

The development project discussed in this paper was conducted with the aim of doing away with factors introducing uncertainty into clamp load control and thus of enhancing the accuracy of clutch torque prediction, in order to allow slip start to be used in races and to obtain a competitive advantage over competitors.

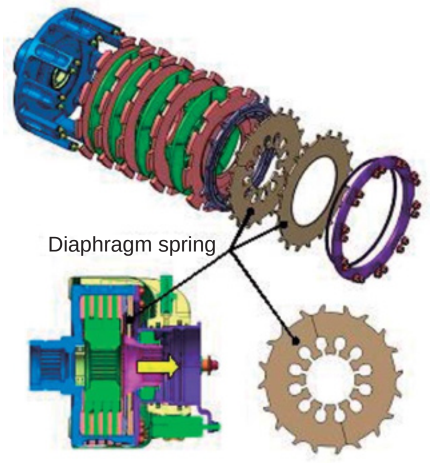

Fig. 1 Pull clutch mechanical section

3. Methods of Achievement of Development Aims

3.1. Development of Direct Push Clutch (DPC) with Lever Plate

Employing a configuration in which the clamp load was obtained directly from hydraulic pressure, the developed system replaced the diaphragm spring used to generate clamp force in the conventional pull clutch with a lever plate (Fig. 2). The lever plate was fixed in place between the foot of the clutch basket and the clutch cover to enable it to produce a return load that would help ensure zero torque. The hydraulic actuator pushed the lever plate, and the lever plate made contact with the pressure plate. The lever plate became a lever with this point of contact as its working point, and a clamp load was generated on the clutch friction material. The clamp load was determined exclusively by the pushing load of the hydraulic actuator and the lever ratio of the lever plate, and there was thus no effect from the characteristics of the diaphragm spring and variations in these characteristics, or variations in dimension due to thermal expansion of the component parts. Because the clamp load was directly determined with the pushing load of the hydraulic actuator as the parameter, the controllability of the clamp load was enhanced, and as a result the accuracy of clutch torque prediction was also enhanced.

3.2. Development of Low-friction Actuator

The reduction of hysteresis in the actuator was an important factor in enabling high-accuracy control of the clamp load using hydraulic pressure to be realized. The major determinant of actuator hysteresis was seal friction, which can be expressed using the following equation:

$$Fr = \mu s \cdot \pi \cdot dp \cdot bs \cdot P \quad (2)$$

Fr: Friction
μ*s*: Friction coefficient of the seal
dp: Piston diameter
bs: Seal width
P: Hydraulic pressure

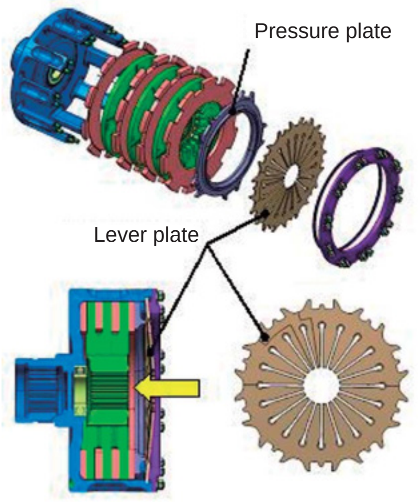

Fig. 2 Push clutch mechanical section

Seal friction is therefore proportional to piston diameter (the seal length), and it can easily be seen that plunger-type pistons present a greater advantage than annular pistons. Taking the friction reduction effect and the potential for prevention of stick by inclining of the piston into consideration, a twin-piston actuator was therefore adopted, reducing seal length by approximately 80% against that of an annular piston (Fig. 3, Fig. 4).

3.3. Clutch Engage System

Engine start was one of concern in using DPC. Because the clutch was fully engaged when the engine was stopped (zero hydraulic pressure) in the conventional clutch system, the engine could be started by externally rotating the layshaft on the gearbox input side, which is positioned coaxially with the crankshaft. However, in the case of a DPC, because no clamp load is generated when the engine is stopped, the crankshaft will not rotate even if the layshaft is rotated.

A clutch engage system (CES) was therefore employed. In this case, a hydraulic pressure storage unit known as a clutch disengage system (CDS), which had previously been used to temporarily disengage the pull clutch to enable a vehicle with a stopped engine to reach a safe stopping point on the track, was used as a system to engage the clutch before engine start.

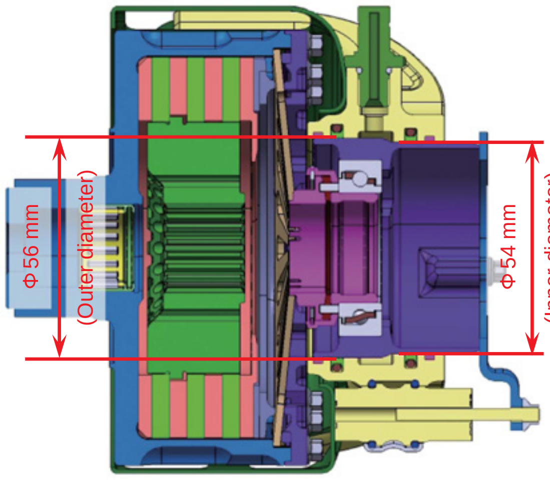

Fig. 3 Push clutch single-piston actuator

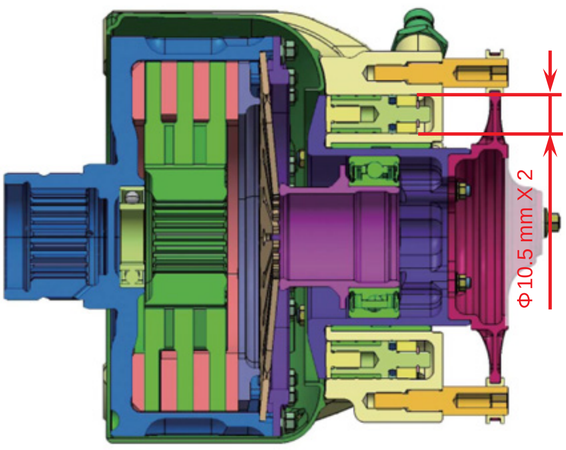

Fig. 4 Push clutch twin-piston actuator

3.4. Organization of Development Process and Allocation of Roles

The development team discussed whether the development process, from clutch to actuator, should be conducted 100% in-house, or whether the development should be conducted in collaboration with a specialist clutch manufacturer. For the reasons listed below, it was decided that the clutch unit would be developed in a joint development with SRE, and that in the case of the actuator, only the parts used in bench tests would be manufactured in Japan and supplied, with the technology of the parts for vehicle tests and race use to be transferred to the race team (HRF1).

(1) The clutch is a consumable part needing day-to-day maintenance. The support from a location close to the race team was therefore judged to be more efficient.

(2) The lead time for manufacturing the carbon material that was used in the clutch was long, and the production of the material in small batches was challenging. In addition, the level of technological challenge was high, and it was therefore decided that in view of the development schedule for the DPC, this aspect of the development should be separated from the DPC project.

(3) In order to incorporate feedback from the race team rapidly, it was judged that transfer to HRF1 would be the most efficient means of maturing the design quickly.

4. Results

4.1. Effect of Use of Slip Start for Race Start

The application of the developed clutch system enabled slip start to be used in the absence of feedback control. Figure 5 compares time for acceleration from 0-100 km/h using slip start and dump start.

A comparison of acceleration times to 100 km/h shows that the use of slip start provided a competitive advantage by helping to enable a maximum time reduction of 0.46 sec, corresponding to a distance of approximately 11 m. This would enable the race vehicle to overtake one lead vehicle by the first corner.

4.2. Characteristics of Clutch Unit

This section will discuss results obtained for the differences in characteristics between the DPC and the

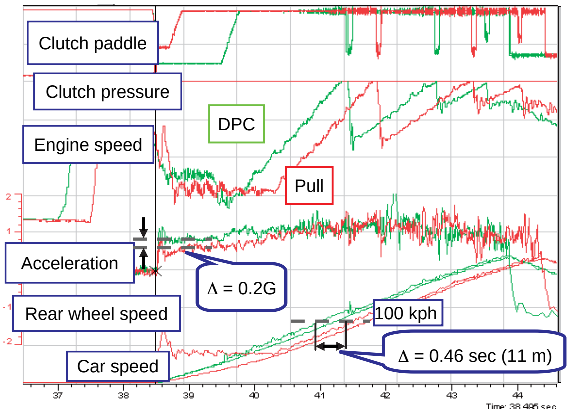

Fig. 5 0 - 100 km/h pull clutch - DPC comparison conventional pull clutch. In the case of the pull clutch, the clamp load of close to 150 daN at race start was in the range for maximum diaphragm spring hysteresis (range of maximum pulling load), and a hysteresis of ±20 daN was generated (Fig. 6). By contrast, the lever plate used in the DPC was employed in an entirely insensitive range to the diaphragm spring characteristic, i.e., a range in which it worked as a lever to amplify the load, and its hysteresis was controlled to around ±10 daN (Fig. 7).

In addition to spring hysteresis, the pull clutch also incorporated other uncertain elements, including changes in the clamp load due to thermal expansion of the constituent parts, variations in the diaphragm spring characteristic, and stroke sensor offset due to heat, which increased the uncertainty of controlling the clamp load.

4.3. Actuator Friction Reduction

Figure 8 shows the results of measurements of clamp load hysteresis against hydraulic pressure for the annular-type single-piston actuator and the plunger-type twin-piston actuator. The twin-piston actuator displayed 80% lower friction in a static test. This is a result of reducing the seal length of the hydraulic piston by approximately 80%.

4.4. Characteristics of System

Figure 9 shows results for the characteristics of the system combining the DPC and the twin-piston actuator. The graph in Fig. 9 plots clutch torque against actuator pressure as measured during tests in circuit simulation mode bench test with an engine. As in the case of the actuator unit tests, torque was output in a linear relationship with hydraulic pressure, with minimal effect from uncertain elements such as wear of the clutch friction material or thermal expansion. These results indicated that the system fulfilled the initial development targets established for it, accurately controlling clamp load throughout its period of use, and helping to enable clutch torque prediction.

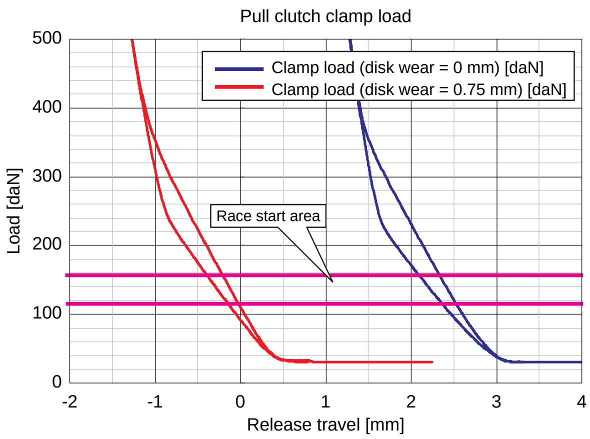

Fig. 6 Pull clutch: Stroke - clamp load

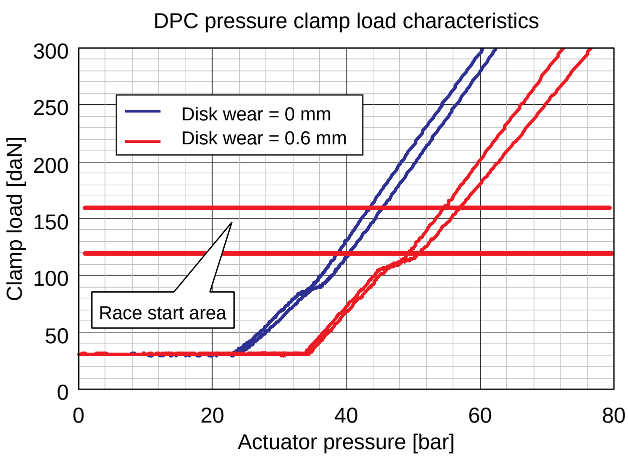

Fig. 7 Push clutch: Pressure - clamp load

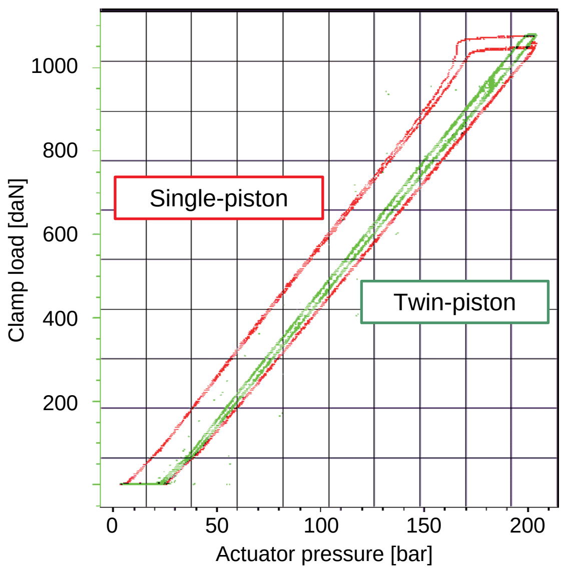

Fig. 8 Actuator pressure - clamp load

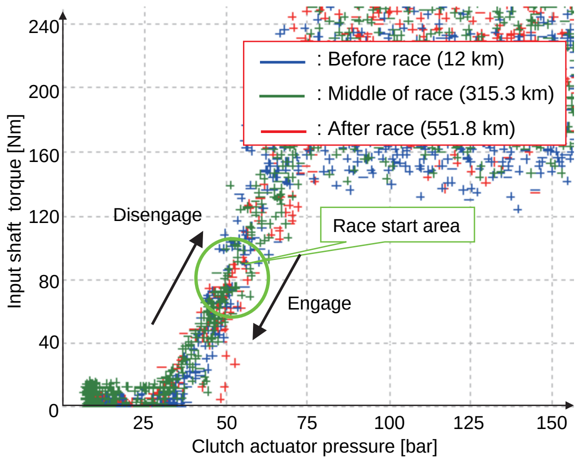

Fig. 9 Clutch pressure - torque

5. Conclusion

Factors resulting in variations in the clamp load and the friction of the seal in the actuator were focused on in order to enhance the accuracy of torque control in a carbon dry multi-plate clutch for use in a Formula One vehicle. The use of a hydraulic direct push mechanism employing a lever plate in the clutch unit and the use of two low-diameter pistons in the thrust load generator of the actuator produced the following results.

(1) A hydraulically-controlled DPC system enabling accurate control of clamp load (clutch torque) was developed.
(2) In 2006, the use of slip start without feedback control was realized, enabling the achievement of a maximum reduction of 0.46 sec (corresponding to approximately 11 m) in time for acceleration from 0-100 km/h.

The following issues for future study can also be indicated.

(1) Variations in clutch characteristics occurred due to friction material wear and the load characteristic of the return spring in the lever plate (Fig. 7). This represents an uncertain element. A wear correction system for the hardware to help ensure that there is no change in the air gaps even when wear occurs would be an ideal solution.
(2) In the range immediately following the generation of the clamp load, a “shelf characteristic” appears by the clearance between the lever plate and the surrounding parts (Fig. 7). This is a factor that increases the complexity of control, and correction of this characteristic is therefore desirable.
(3) While a great deal of research has been conducted on the subject, the friction coefficient of the carbon disk, another element that determines clutch torque, is at present not fully understood. The prediction of the friction coefficient is a major theme in research aimed at producing ideal clutch systems.

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