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# Development of Seamless Shift for Formula One Car

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## ABSTRACT

Honda focused on gearbox development during its third Formula One era. The reduction of shift time is an effective means of maximally increasing race competitiveness within the constant-mesh 7-speed gearbox regulations. In the standard shift process, the current gear was disengaged, the system went into a neutral state, and the following gear was engaged. Honda's seamless shift realized up-shift with a torque loss time of zero, by engaging the following gear and then disengaging the current gear. Normally, this process would lead to damage due to double engagement, but in the developed system double engagement was prevented and transmission of deceleration torque was enabled by adding one-way clutches with a locking function to the conventional shift mechanism. The selective use of these one-way clutches, positioned between the gear hubs and the mainshaft, and the use of cooperative control with the engine, enabled the realization of seamless shift across the entire shift range. As a result, lap time was reduced by 0.4 sec per lap, and the system was used in races from 2005 as the first shift mechanism of its type in the Formula One world.

This paper will also discuss the removal of the shift forks and shift rings as well as the fitting of the gear selection mechanism inside the mainshaft in order to reduce the total length and weight of the mechanism while maintaining its seamless shift performance.

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## 1. Introduction

The shift mechanisms used in Formula One vehicles are constant-mesh parallel twin shaft types, in which gear stages are changed using dog clutches of the type frequently employed in motorcycles. In the project discussed in this paper, a shift mechanism was modified at the initial stage of gearbox development in order to boost the competitiveness of Formula One vehicles. The development aim established to realize this goal was to reconcile rapid shift (reduced shift time) with secure shift (durability and reliability). In order to realize rapid shift, acute chamfer angles were employed in the dog clutches, barrel inertia was reduced, and the speed of operation of the shift system was increased. The increase in shift speed generated a number of issues, including operational irregularities originating in shift fork overshoot and inclination of the shift rings. In order to prevent these issues, the forms of the barrel cams and the shift forks were optimized to stabilize shift operation. This helped to realize an equivalent level of competitiveness with the vehicles of other teams, but innovative technologies are essential to achieving victory in the fast-evolving world of Formula One racing. In

conventional shift mechanisms, it was necessary to reduce engine torque to close to zero during up-shift, and the time of deceleration produced by the air resistance of the vehicle had a significant effect on performance. However, further reductions in shift time could not be expected using this type of mechanism. The ultimate goal for attempts to reduce shift time is the realization of shift with no torque loss. It was assumed that achieving this within the regulations would involve a variety of issues, but it was also considered to represent an excellent opportunity to increase Honda's competitiveness against other teams, and a development project was therefore commenced.

## 2. Development Aims

Shifts using one-way clutches, as are often employed in automatic transmissions in mass-production vehicles for shift from 1<sup>st</sup> to 2<sup>nd</sup> gears, enable at least one shift with no torque loss. The development aim established for the project was to realize seamless shifts by developing a shift mechanism in which this function could be applied to all the gear stages in a Formula One vehicle gearbox.

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### 3. Methods of Achieving Development Aim

#### 3.1. Alteration of Dog Clutch Engagement Timing

In a conventional shift mechanism, when torque is acting on the dog clutches, friction on the dog clutch coupling sections prevents shift (engagement and disengagement of the dog clutches). Because of this, during shift the engine torque was reduced, and the dog clutch of the current gear stage was disengaged. When this operation was completed, the dog clutch of the next gear stage was then engaged simultaneously with the recovery of engine torque. However, the engagement of the dog clutch of the next gear stage while the current gear stage was still transmitting torque, and the disengagement of the dog clutch of the current gear stage after the next gear stage commences transmitting torque (when the current gear stage has ceased transmitting torque) would enable shift with no drop in engine torque. Figure 1 shows the difference in dog clutch engagement timings for shifts from 5<sup>th</sup> to 6<sup>th</sup> gears in the conventional and seamless shift mechanisms as an example. As the figure shows, in conventional shift there is a neutral state between the stages, while in the seamless shift, the dog clutches for both 5<sup>th</sup> and 6<sup>th</sup> gears are engaged.

#### 3.2. Prevention of Double Engagement during Up-shift

As Fig. 1 shows, if this shift timing is applied using the conventional shift mechanism, there will be a period during which the current gear stage and the next gear stage will be engaged simultaneously, i.e., double engagement. It is widely known that double engagement may cause issues that make the vehicle inoperable. A mechanism enabling double engagement to be prevented was therefore developed for the new system. Figure 2 shows the configuration of the parts of the seamless shift mechanism. Figures 3 and 4 show the movement and function of each of the parts during up-shift.

Figure 3 shows the parts during acceleration, as seen from the front. The direction of rotation is counterclockwise. Torque from the engine is transmitted

to the clutch, the lay shaft gear, the mainshaft gear, the shift ring, the gear hub, the strut, and the mainshaft, and is output to the tires. In a conventional shift, the gear hubs and the mainshaft are connected by splines, but the seamless shift mechanism employs struts that function as one-way clutches between the gear hubs and the mainshaft.

Figure 4 shows a state of double engagement, when the next gear stage has commenced transmitting torque and the dog clutch of the current gear stage is still engaged, during up-shift using the seamless shift mechanism.

When the dog clutch of the next gear engages and the gear commences transmitting torque, the rotation of the next gear stage becomes faster than that of the current gear stage, and the strut of the current gear stage is taken into the mainshaft pocket inside the gear hub where it functions as the idling side of a one-way clutch, enabling double engagement to be prevented. Because

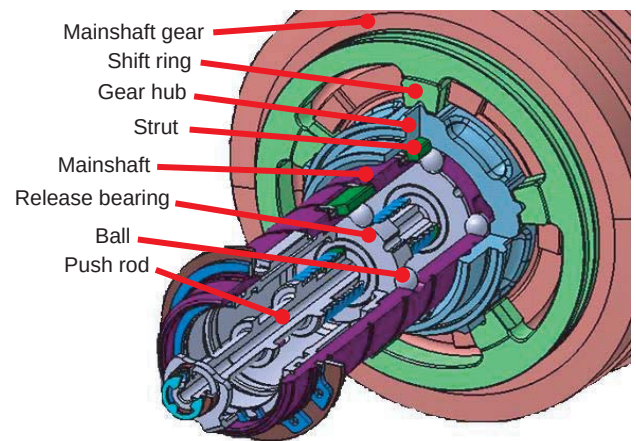


Fig. 2 Parts configuration of seamless shift mechanism

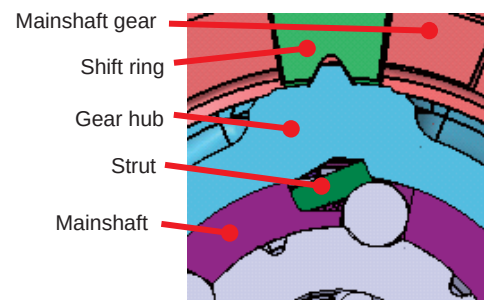


Fig. 3 Up-shift state

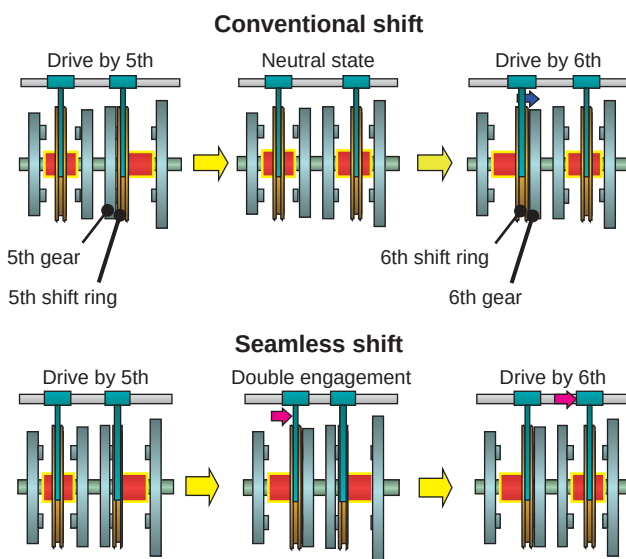


Fig. 1 Dog engagement timing

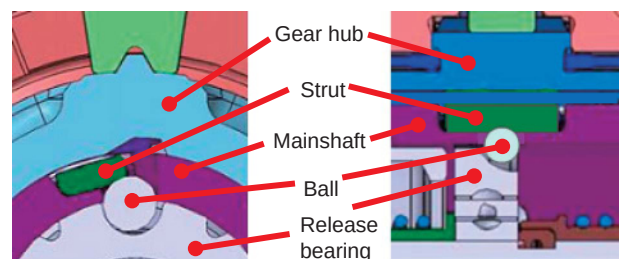


Fig. 4 Ratcheting state

the current gear stage is no longer transmitting torque, the shift ring can be released from the dog clutch without causing engine torque to drop, enabling the realization of seamless shift.

The strut of the next gear stage engages automatically with the gear hub due to centrifugal force, and functions as the engaging side of a one-way clutch.

### 3.3. Engine Brake

This simple one-way clutch mechanism using the struts enables torque transmission during acceleration, but it is unable to transmit torque during braking. In order to resolve this issue, a ball is inserted beneath the strut in order to lock it, enabling deceleration torque to be transmitted. Figure 5 shows the system during application of the engine brake. The path of deceleration torque is opposite to the torque path during acceleration. The input from the tires is transmitted to the driveshaft, the differential gear, the bevel gear, the mainshaft, the ball, the strut, the gear hub, the shift ring, and the mainshaft gear, and is finally input to the engine. The release bearing is locked or released by a pushrod.

### 3.4. Downshift

The new system features the following major differences from a conventional shift mechanism to enable the realization of seamless shift:

- (1) A shift barrel profile enabling a double engagement timing to be obtained
- (2) A mechanism enabling double engagement to be prevented

To enable downshift using mechanisms that focus on up-shift, when the release bearing has been released and the system has downshifted from the current gear to the next gear, the release bearing is locked again. In order to release the release bearing, it is necessary to reduce torque. This method increases the length of time that deceleration torque is reduced against a conventional shift mechanism. A shift barrel profile enabling downshift without releasing the release bearing was therefore proposed in order to achieve downshift in the same short period as a conventional shift mechanism while realizing seamless up-shift. Figure 6 shows the shift barrel profile during up-shift. The shift rings and the dog clutches engage when the shift fork stroke reaches 39% or more, and the diagonally-shaded area in the figure therefore represents a state of double engagement.

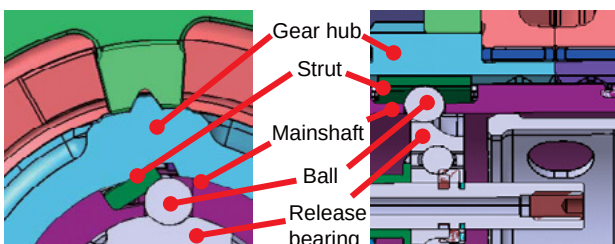


Fig. 5 Overrun state

Figure 7 shows the shift barrel profile during downshift. The diagonally-shaded area in the figure shows the system in a neutral state. This neutral state enables downshift with the release bearings locked.

This shift barrel profile also features free areas, in which the shift forks move freely. These are shown as the vertically-shaded areas in the figures. Unwanted movement of the shift forks has been prevented by positioning détente springs between the selector rails and the shift forks. The engagement and disengagement of the dog clutches on the up-shift and downshift sides at different timings has enabled the reconciliation of the desired up-shift performance with downshift in the same time period as a conventional shift.

## 4. Effects

The time-chart of engine speed, engine torque, and wheel speed during up-shift were compared in order to verify the effects of the seamless shift mechanism developed in this research. Figures 8 and 9 show data for conventional shift and seamless shift respectively. The seamless shift realizes up-shift while maintaining engine torque, enabling shift to be completed with no loss of drive power. In a bench test simulating the Silverstone Circuit, figures of 4 km/h when converted for speed and 7.6 m when converted for distance at the end of the home straight were obtained. The new mechanism was employed in races from the 1st race of 2005.

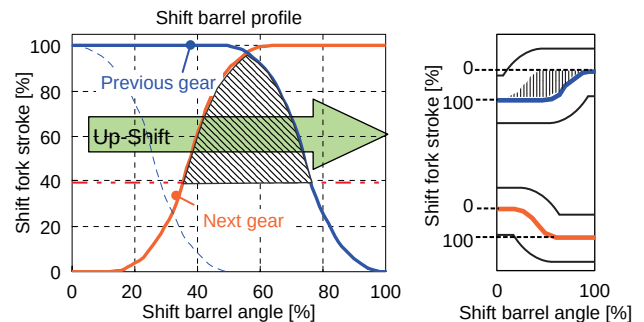


Fig. 6 Up-shift shift barrel profile

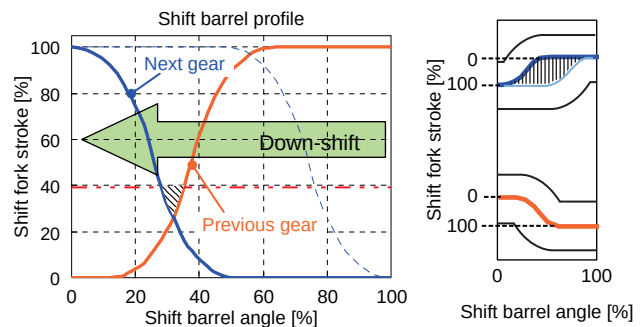


Fig. 7 Down-shift shift barrel profile

## 5. Evolution

### 5.1. Further Development Aims

Honda led the world in introducing the seamless shift mechanism, but by the end of the following season, almost all other teams were adopting systems that offered the same benefits, and Honda's advantage from the perspective of shift performance had weakened. The system had maximally increased performance in terms of preventing torque loss during acceleration, but Honda's gearbox fell behind those used by the other teams from the perspectives of weight and compactness. A development program was therefore conducted with the aims of making the system more lightweight and compact while maintaining the same level of shift performance.

### 5.2. Mechanism

#### 5.2.1. Salient features

An in-shaft shift mechanism was developed that positioned one-way clutches able to control torque transmission and idling between all the shift gears and the mainshaft, and that was fitted within the mainshaft. Doing away with the shift forks, shift rings, gear hubs, and other equipment, which were conventionally positioned between the shift gears, and using only shift gears arrayed in a line enabled the total length of the

gearbox to be reduced. At the same time, the weight of the gearbox itself was reduced (Figs. 10 and 11).

#### 5.2.2. Configuration

The in-shaft shift mechanism features an operating range in which double engagement is used, and the principle of preventing torque loss is the same as that used by the seamless shift mechanism discussed above. However, the configurations of the shift mechanisms differ significantly. This section will discuss the parts forming the mechanism and the roles of those parts. Figure 12 shows the shift mechanism, including shift gears. Each strut positioned between a shift gear and the mainshaft moves in a seesaw fashion by means of small and large balls, producing the following three essential states for shift:

- (1) An in-gear state, in which a strut simultaneously engages and is locked in place, enabling acceleration and deceleration torque to be transmitted (Fig. 13)
- (2) A neutral state, in which the angle between the struts and the mainshaft in the circumferential direction is smaller than it is in the in-gear state and the gears and

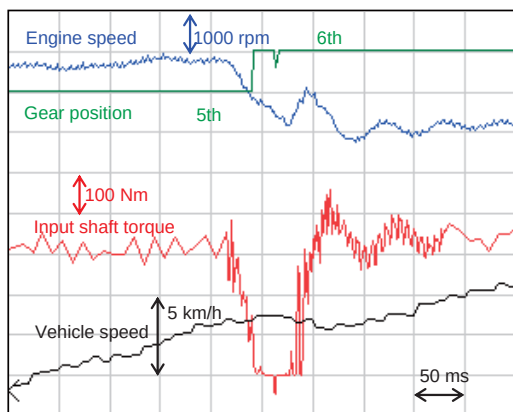


Fig. 8 Data for conventional shift

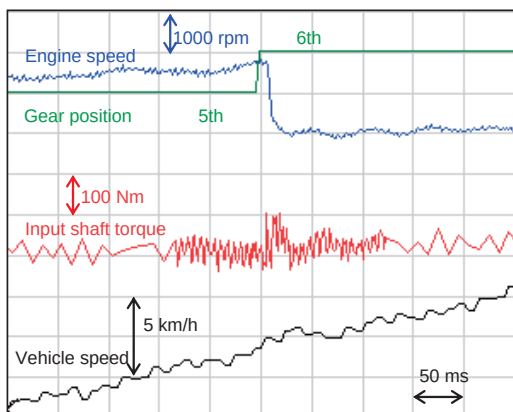


Fig. 9 Data for seamless shift

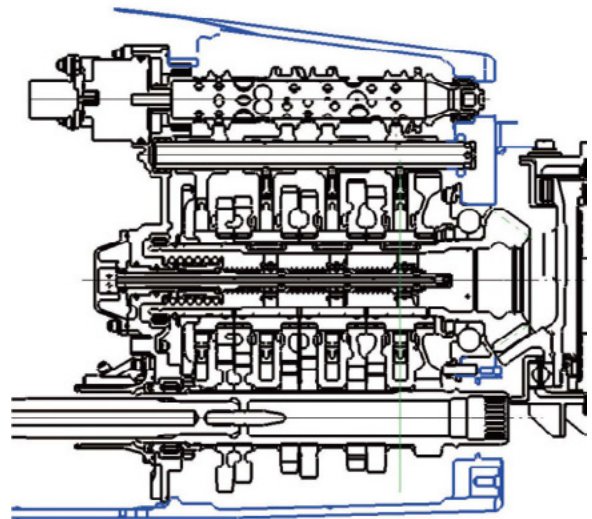


Fig. 10 Conventional seamless shift

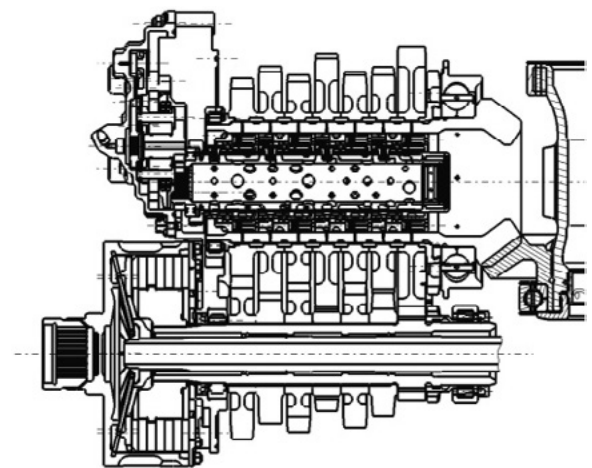


Fig. 11 In-shaft seamless shift

mainshaft idle during both acceleration and deceleration (Fig. 14)

- (3) A one-way state, in which only acceleration torque is transmitted (Fig. 15)

The state of the struts is controlled by the positions of two large and small balls in the radial direction. The positions of the balls are adjusted by the movement in the axial direction of a slide cam that is provided with a cam groove in the axial direction designed specifically for use with the balls. The movement of the shift bearings in the axial direction adjusts the position of the slide cam in the axial direction by means of a spring. The position of the shift bearings in the axial direction is adjusted by the movement in the axial direction of a pin integrated with the shift bearings, which follows a barrel cam groove formed on the inside of the shift bearings in the circumferential direction. As a result, it is possible to selectively control the three states of the struts by means of barrel rotation.

### 5.2.3. Operation

The process of shifting from the current gear to the next gear is as follows:

- (1) When the current gear is driving, the current gear is in an in-gear state, and all the other gears are in neutral states.
- (2) Shift is commenced by the rotation of the barrel; the struts of the current gear and the next gear are put in one-way states simultaneously.
- (3) When torque transmission shifts from the current gear to the next gear, the strut of the current gear, which has ceased transmitting torque, is put in a neutral state.
- (4) The next gear is put in an in-gear state, and shift is completed.

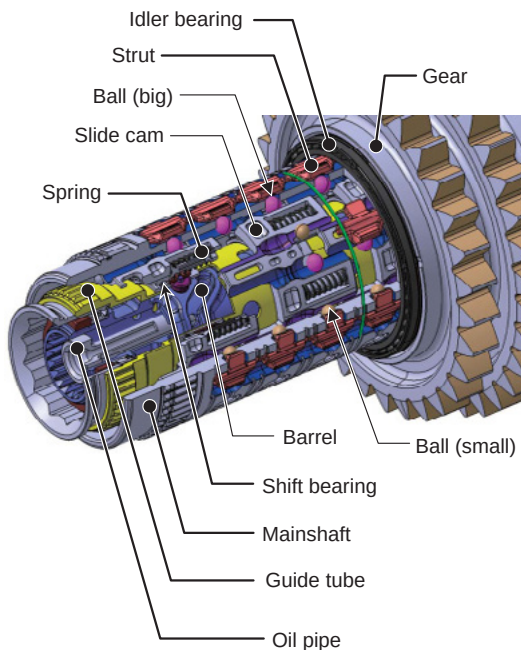


Fig. 12 Parts configuration of in-shaft seamless shift mechanism

Figure 16 shows the timing of in-gear states for up-shift and downshift. “a” shows the disengagement timing of the current gear during downshift, “b” shows the engagement timing of the next gear during up-shift and downshift, and “c” shows the disengagement timing of the current gear during up-shift. Different timings are necessary for the disengagement of the current gear during up-shift and downshift. This is necessary for the same reason as was the case for the seamless shift discussed above, but the method of achieving it differs

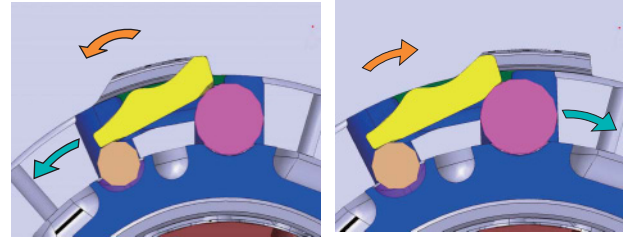


Fig. 13 In-gear state

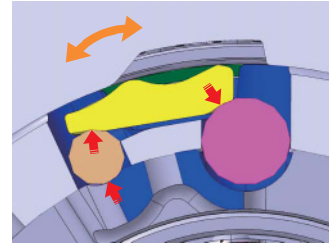


Fig. 14 Neutral state

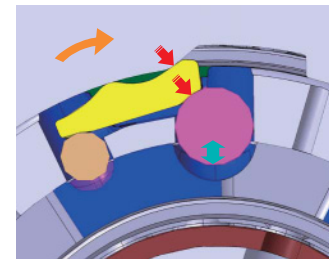


Fig. 15 One-way state

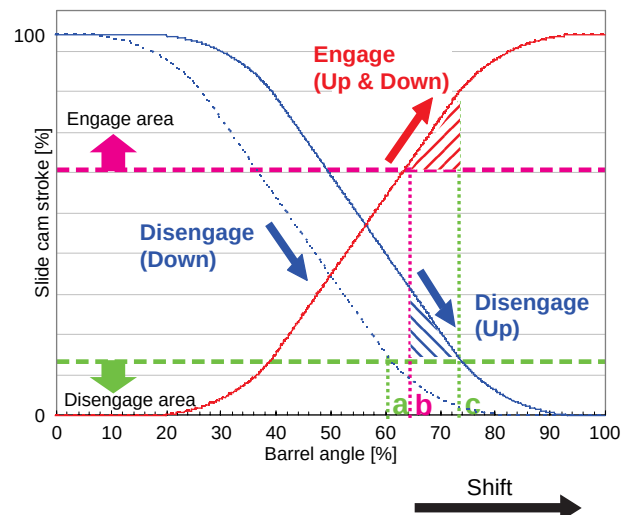


Fig. 16 Shift timings

for reasons of space. In the new system, the different timings are enabled by positioning springs between the slide cams and the shift bearings. During up-shift, the strut of the current gear cannot be disengaged until the current gear has ceased transmitting torque. By means of compressing the spring even when the barrel is rotating, the movement of the slide cam is delayed, and as a result the transition to a neutral state is delayed, thus creating a range in which double engagement occurs. During downshift, because a load is applied in the direction of disengagement of the strut, the transition to a neutral state can be made with no delay in the rotation of the barrel against the movement of the slide cam, thus enabling double engagement to be prevented.

#### 5.2.4. Effects

The employment of the newly developed in-shaft seamless shift mechanism has reduced the total length of the mechanism by 19% (from 192.7 mm to 155.1 mm) and the weight of the mechanism by 12% (from 10.4 kg to 9.1 kg) against a conventional shift mechanism.

#### 5.3. Verification of Performance and Reliability

Shift performance figures for the in-shaft seamless shift mechanism were identical to those for the seamless shift mechanism, shown in Fig. 9. The new system was being used under the four-race gearbox regulation introduced by the FIA in 2008, making it important to verify reliability. Bench tests were commenced on the system, but Honda then announced its withdrawal from Formula One racing, and the development project was discontinued when the tests had reached the 1300 km mark of a projected 2500 km.

## 6. Conclusion

A shift mechanism that has a modified shift sequence to prevent torque loss during up-shift and selectively uses one-way clutch mechanisms to prevent double engagement was realized within the scope of Formula One regulations. This development produced the following outcomes:

- (1) As the first shift mechanism of its kind in the Formula One world, the new system enabled lap times to be reduced by 0.4 sec per lap, and was used in races from 2005.
- (2) The realization of up-shift with no torque loss and minimal torque fluctuation during shifting enabled shifting in situations of low tire grip, such as when cornering or during rainy conditions.

The quest for increased compactness while maintaining seamless shift performance by removing the shift forks and dog rings and fitting the mechanism inside the shaft enabled the total length to be reduced by 19% and weight to be reduced by 12%.

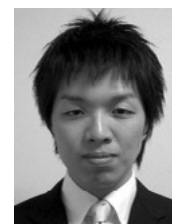
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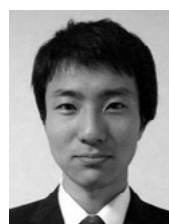
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