
Overview of Gearbox Development for Formula One

Atsushi MANO*

ABSTRACT

In the racing world, the transmission is ordinarily referred to as the gearbox. Honda first tried developing an Formula One racing gearbox with its third-era Formula One activities. To do this, it was necessary not only to develop the technology, but also to solve several problems, including production, supply and operation. This article recounts how Honda overcame these problems to bring a number of technological firsts to the racing world and gives an overview of the advancement of Formula One gearbox technology.

1. Introduction

Generally, when people talk about Formula One technology, engine power and aerodynamic performance are often mentioned, but there are few opportunities to bring up gearbox technology. This article, therefore, will start by discussing the basic elements essential to gearboxes and recount how Honda's development advanced these elements.

2. Formula One Gearboxes

2.1. Regulations

The following is a brief excerpt (not a verbatim quotation) from the Formula One technical regulations on transmissions as stipulated by the Federation Internationale de l'Automobile (FIA).

- (1) Only two-wheel drive is allowed
- (2) It must be possible to cut the clutch manually when the vehicle is stopped

In the event that a vehicle stops along the course because of vehicle trouble or any other reason, course attendants must be able to push it out of the way, so vehicles have a manual clutch cutoff switch that even works when the engine is shut off.

- (3) The minimum number of forward gear ratios is four and the maximum is seven, and CVT is prohibited
- (4) Vehicles shall have a reverse gear
- (5) Left/right torque transfer is prohibited

In addition to the above, the following rules were added in 2008 to control costs.

- (6) A single gearbox must be used in four consecutive races
- (7) Gear ratio pairs must have a minimum thickness of 12 mm wide with at least 85 mm between centers, and each set of gears must weigh at least 600 g

Other than the parts newly established to avoid excessive technical competition, these restrictions are only a general framework, and there is overall a very high degree of freedom in the design of gearboxes. Because of that, each Formula One team is aggressively developing technology with the major objectives being lightness, compactness and high efficiency.

2.2. Required Performance

The following lists the performance required of a Formula One gearbox.

- (1) Durability and reliability
- (2) Lightness and compactness
- (3) Lower center of gravity and low yaw inertia moment
- (4) Quicker gear shifting
- (5) High transmission efficiency
- (6) Stiffness of casing

Unlike mass-produced vehicles, the rear suspension is directly attached to the casing (Fig. 1), so sufficient

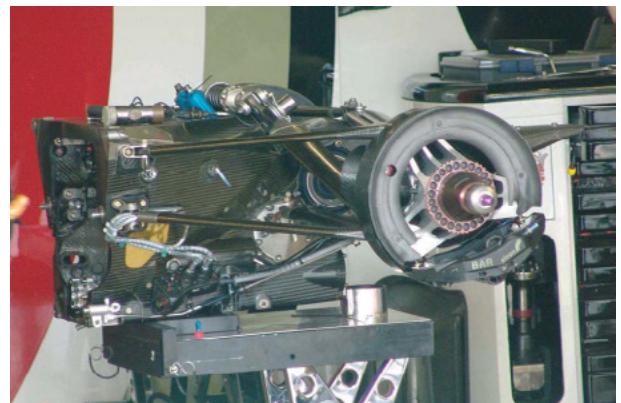


Fig. 1 Appearance of F1 gearbox

* Automobile R&D Center

stiffness and strength are required, and this has an impact on vehicle behavior.

(7) Must contribute to aerodynamic performance

The gearbox must be as small as possible so that it does not impede airflow to the rear wing and diffuser at the back of the vehicle. In particular, the rear part must be narrow.

(8) Easy to maintain

It must be possible to complete ratio gear changes in the interval between racing sessions.

In addition, the internal mechanism transmits engine torque input through the clutch through seven sets of gears, a bevel gear and final gear, as shown in Fig. 2, and from there through the drive shaft to the tires.

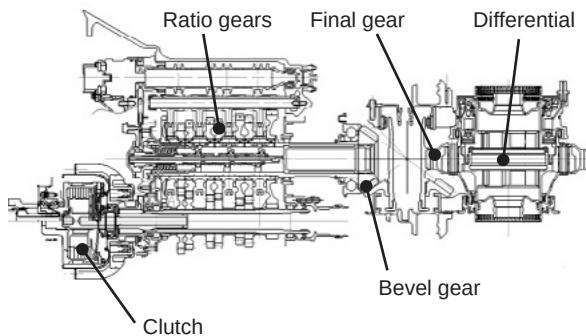


Fig. 2 Structure of F1 gearbox internals

3. Preparation for Original Development

3.1. Establishment of Joint Development Partnership with Racing Team

Honda's third-era activities began in the form of joint development of racing cars with British American Racing (BAR). Because development of the gearbox was mainly done by the race team BAR, the first issue to resolve was how to proceed with joint development. The development conducted by BAR at the time was on the part concerning the overall package, including the casing, while detailed design and production of internal components like the gear shaft were contracted out to manufacturers specializing in racing transmissions. Therefore, although BAR was able to present its requirements relating to gear and shaft layout, it was difficult to make these parts lightweight and develop innovative mechanisms faster than other teams, and even if it came up with good ideas, it was difficult for BAR to use them exclusively. On the other hand, Honda's strengths were its ability to manufacture casings, gears and shafts internally and the fact that it had bench testing equipment to evaluate the strength and reliability as well as performance of gearboxes, something which other racing teams at the time did not have. If Honda therefore could provide its competitive technology in place of the specialized manufacturers, the advantages to BAR would be significant, such as being able to develop pioneering technologies and use them exclusively. For that reason,

the two sides agreed that Honda's Tochigi Automobile R&D Center (HGT), a development base in Japan, would oversee development of technology, especially for gears and shafts, and full-scale development began in HGT in 2002. Subsequently, development continued with the same division of responsibilities even after the team reorganized into the Honda Racing F1 Team (HRF1) in 2006.

3.2. Learning Formula One Gearbox Development Technology

Before development could proceed, Honda first had to learn the level of technology in Formula One gearbox. The following four major issues had to be addressed in order to do this.

(1) Design engineering

As for the type of gear, mass-produced automobiles use helical gears, where the emphasis is put on gear noise. In contrast, racing cars use spur gears, with more emphasis on efficiency and strength. Although there are differences, the design tools are the same, and the basic design techniques of the former could be used in the latter. The conditions under which racing cars are used, however, made it impossible to use the historical data from mass-produced automobiles as reference, and Honda learned that it is necessary to deal with early onset gear surface pitting and to make revisions to gear teeth tips, taking into account elastic deformity of the gear teeth caused by impact load input from such forces as shift shock.

(2) Production technology

In order to ensure gear strength and maximize transmission efficiency, all gears underwent heat treatment and subsequent gear grinding (that is, grinding of the entire tooth down to the bottom), and then for the surface finish underwent a treatment to reduce surface roughness of the tooth (including barrel grinding) and shot peening to enhance fatigue strength. In particular, the grinding process required numerous rounds of trial and error and new arrangements in order to get the same level of surface roughness as the specialist manufacturers' gears, which were used as reference. In addition, during shot peening, in order to give the material areas with higher surface residual stress and deeper residual stress, Honda had to spend much time catching up to the specialist manufacturers' performance, not only selecting media but using multistage shot and choosing the right process pressure and times.

(3) Materials technology

The gear materials that were being used in the racing industry were the same materials used in mass-produced gears but with extra strengthening, and to be competitive it was necessary to develop specialized high-strength gear material. Honda worked with steel manufacturers and had to spend many hours until it could get satisfactory material performance.

(4) Preparing a cooperative prototype production system

To develop competitive technology in timely fashion, one absolutely must have production support in the form of fast prototype-production times by a number of

manufacturers specializing in the area of prototype production. Honda received support from many proven prototype producers of gears and was able to manufacture gears and shafts with relative ease, but it faced more difficulty in prototype-producing bearings. When developing new gearboxes for racing purposes, the use of bearings of a specialized form contributes to performance enhancement. Bearings, however, are highly specialized functional components, and there are no manufacturers who prototype-produce them. As a result, Honda had to depend on manufacturers of mass-produced bearings to prototype-produce some, but the manufacturers had difficulty meeting Honda's need for small quantities of many types, so the prototype-production period grew longer and there were frequent situations where the manufacturers could not meet Honda's development needs. However, thanks to development support from NTN Corporation, Honda was able to build a cooperative development system for Formula One bearings. As a result, the time from examination of specifications to prototype production and supply of components was shortened and it was possible to work in a timely manner.

3.3. Technical Development Goals

To address the issues mentioned in the preceding sections and ensure competitiveness in the area of gearboxes, the major development goals were narrowed down to the following two, which are big factors in lap times.

(1) Lightness and compactness

Regulations dictate that racing vehicles must weigh no less than 605 kg, including the driver, so a lighter gearbox does not lead directly to a lighter vehicle. However, by increasing ballast weight to adjust overall weight, one can try to increase the degree of freedom for vehicle weight distribution and lower the center of gravity. Also, greater compactness not only leads to lighter weight but also enhances aerodynamic performance by giving the gearbox a slim form. These contribute to the vehicle's competitiveness.

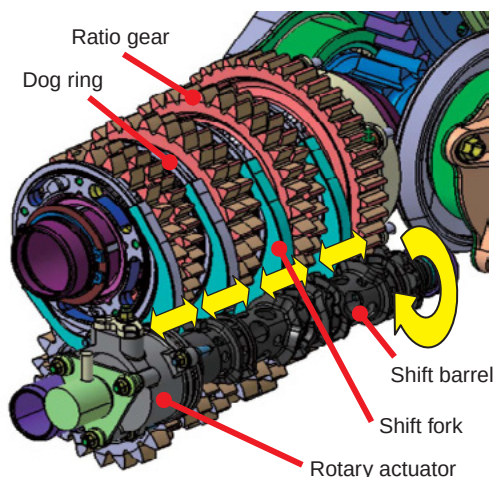


Fig. 3 Appearance of F1 gear-change system

(2) Faster gear shifting time

Beginning in the early 1990s, Formula One autos used a sequential shift mechanism consisting of a dog clutch and a shift barrel driven by a hydraulic actuator, as shown in Fig. 3, a system that works on the same principle as that used in motorcycles. Particularly when upshifting during acceleration, the vehicle can decelerate with a force of as much as 1.0 G from air resistance because of interruption of torque delivery, so reducing shifting time is a crucial objective directly linked to better lap times.

3.4. Establishment of Racing Component Supply System

In order to bring competitive, unique technologies, one must not only develop those technologies but also produce and supply the number of components needed for operations with stable quality. Prior to this development, Honda had supplied assembled complete engines to a race team, but this was its first experiment supplying individual components. For that reason, it was necessary to create a system, including the organization, in order to achieve the two following points.

(1) Production quality assurance

For those important components associated with the driving function, the history of each component is controlled (this includes control of production lot and driving lifecycle). For this purpose, the part number, serial number and production lot are controlled. Infrastructure needs to be prepared so that this information can be placed directly on components by laser marking. Honda has not only introduced a laser marker, but also established rules, routes and a system for conducting this work.

In addition, it was necessary to attach an inspection report card to each component as evidence that it satisfied blueprint quality. To do this, Honda arranged inspection systems for all components and decided on serial number engraving and key point control dimensions. Honda additionally established rules for writing concession reports on rescue measures for components slightly outside the tolerance which were judged to be no issue functionally, and a system was set up at both HGT and HRF1 to determine whether components presented any functional issues, and if so, to rescue them. This effort sought to prevent unnecessary cost increases and stabilize component supply.

(2) Component shipping system

Since HGT did not previously have a shipping function for individual components, Honda prepared the processes from packaging to shipping of finished individual components. To make sure that ratio gears, final gears and so on could be efficiently stored and assembled at the factory or circuit, Honda created special packing boxes designed to prevent rust, cushion impact and simplify component identification.

4. Details of Technical Advancement

Competition among racing teams to develop

technology has caused gearbox technology to evolve during the third-era Formula One activities. This section introduces and reconsiders the details of this advancement, looking at changes in the trends at other teams and specific technologies worked on at HGT.

4.1. Casing

Since the casing also functions as part of the chassis, it must be highly stiff as well as lightweight. Techniques used by Honda to achieve this were research into a variety of materials and development of production methods. In the past, sand casting of aluminum alloys and magnesium alloys was standard procedure, but in recent years the paths that racing teams have chosen have gone in two different directions^{(1), (2)}. The first path is to advance the casting production methods and save weight by casting with thinner walls. This approach, which used rapid prototype technology, makes the walls thin and at the same time, since there are no restrictions on draft or undercut, it is possible to eliminate useless material. Aluminum or titanium is chosen as the casting material. The second path is to use carbon fiber reinforced plastic (CFRP) as shown in Fig. 4. CFRP can offer the advantage of much greater specific stiffness than metal materials and is also superior in terms of both lightness and stiffness. It takes a long time to manufacture, however, and the production cost is disadvantageous compared to casting. As of 2008, the various racing teams' production methods have diverged into the two methods mentioned, and there is no evident trend of unification to one or the other. At HGT, the engineers worked to develop a lightweight magnesium casing using a CAE program to optimize stiffness, and this was released at the end of the 2002 season. BAR, however, developed a CFRP casing that could be made even lighter, which was put into use starting in 2004, so HGT stopped developing casings.

4.2. Gears

To procure gears, the top teams set up their own technology development environments in which gears were designed and produced internally. In contrast, lower

ranking teams procured gears from specialty manufacturers. Internal mechanisms standardized for Formula One use were customized into packages for each team's vehicle. As stated above, greater compactness of the gearbox itself contributes significantly to the vehicle's competitiveness, and therefore active initiatives have been taken to reduce the size of gears. Techniques for doing this include using high-strength gear material, optimizing the safety factors by using FEM, and advancing the production methods. HGT pursued independent development starting with the gear material, and by enhancing root bending strength and tooth surface pitting strength, it was able to reduce gear width by 1 mm for first through third gears and by 2 mm for fourth through seventh gears, as compared to the gears produced by a specialty manufacturer which had been the base up to that point. This also reduced total gear weight by approximately 1 kg. The new gears were released with the final stage of the 2003 season and thereafter were the standard. At first there was some unexplained gear tooth damage (breakage from the root), but analysis revealed the mechanism: shock loads more than anticipated while gear shifting and sudden changes in vehicle behavior caused some gear teeth to undergo plastic deformation, lowering fatigue strength, and causing breakage in a short span of time. As a result, design standards were established and applied to prevent tooth deformity in ordinary use. In terms of design, however, increasing strength and reducing weight are contrary to each other when dealing with greater than anticipated inputs, and this reduces competitiveness. Therefore, the engineers developed controls to keep excessive input from occurring, and by integrating torque sensors they put a system in place to monitor input values on gears at all times, so that if a gear underwent more than the allowed torque, that gear would not be used again. This effort helped to reduce gear weight in balance with gear strength. The engineers used a gear tester to identify the torque at which tooth bending occurred and found the correlation to design stress, which made it possible to set a highly precise design allowable stress.

4.3. Gear Shifting Mechanism

The sequential semi-automatic gearbox that appeared in the early 1990s became established as the basic structure, with no change until recent years. In the meantime, attempts to reduce gear shifting time focused on reducing operating time by reducing component weight and friction, and on torque optimization control by means of cooperative control with the engine, but no great progress was made. To achieve faster gear shifting times, one of their key development goals, the HGT engineers developed a seamless gear-change mechanism which eliminated interruption of torque delivery while shifting. Theoretically, this mechanism allows the change in gears to take place instantly by letting the next gear engage while still driving at the previous gear. Broadly speaking, there are two major issues involved as described below to achieve this, and the Honda engineers



Fig. 4 Appearance of CFRP gearbox casing

dealt with each of them.

(1) Avoiding interlock from double engagement of gears

Interlock generally results when engaging two gears simultaneously, which causes gear or shaft damage. To make double engagement of gears tolerable, therefore, a one-way clutch structure was incorporated, enabling the one-way clutch to idle even when the former gear switches to a deceleration tooth surface after selecting the next gear, and making it possible to avoid interlock. However, if a one-way clutch is always in operation, issues occur, such as being unable to use the engine brake during deceleration, so the one-way clutch is locked except when shifting, which prevents it from idling.

(2) Increase in shock while gear shifting

Instant gear shifting causes instant change in torque equivalent to the change in inertia based on the gear ratio, so that spike torque increases, in addition to the engine torque. In response, since a major portion of the change in inertia is engine inertia, the engineers reduced spike torque by developing optimization control over the amount of clutch during gear shifting. Combining this control with the mechanism described above made it possible to achieve both this objective and gear strength.

Results of repeated bench tests and circuit tests indicated that these issues had been resolved, so the technology was used in races starting with the 2005 season. Lap times dropped by 0.4 seconds per lap, a very significant advantage for a single technology. Moreover, with no interruption of torque delivery while upshifting and with reduced spike torque, there was less drive fluctuation while shifting and it became possible to shift even while cornering or when there was low tire grip, such as in rainy conditions. Honda was the first to use this technology for eliminating interruption of torque delivery when shifting in a race, but since it was so effective, other teams began eagerly developing the similar technology, so that by 2008 all teams were using it as seamless shifting. It is said that the structure used by other teams, however, had two shift barrels, with the even-numbered gears and odd-numbered gears controlled separately. In contrast, the structure used by Honda consisted of just one shift barrel and was unique in that it prevented double engagement of gears, giving it superior reliability and lightness.

The engineers furthermore undertook to develop an innovative gear shifting mechanism with the goal of producing a technology to reduce the overall length of the gearbox. As Fig. 2 shows, the length of the gearbox can be broadly divided into the clutch, ratio gear, bevel gear, final gear and differential portions. Here, the engineers focused on shortening the ratio gear portion and began a series of investigations based on the idea of eliminating the dog ring and shift fork located between gears. The result they hoped to achieve was a structure that, without losing the advantage of seamless shifting, would reduce overall length by 19% and weight by 12% by putting the shifting components inside the main shaft and aligning the ratio gears without any gap. Although it was difficult to ensure durability of an

internal shifting mechanism, the given target performance was achieved as a result. It had been decided to use this technology in circuit tests at the end of 2008, but this plan was canceled when Honda decided to withdraw from Formula One racing.

4.4. Clutch

In order to maximize launch performance at the start of races, development was begun with the goal of stabilizing clutch transmission torque. Conventional mechanisms controlled clamp load against clutch friction material by adjusting the piston force that hydraulically operates the preload set by the diaphragm spring. This structure made it difficult to control launch torque with much precision because individual assembly statuses caused variance in the clamp load, and wear of the friction material caused diaphragm spring characteristics to change. Figure 5 shows the Direct Push Clutch (DPC) that was developed to address this. By using this mechanism, the clamp force of the friction material was acquired directly from the hydraulic force, eliminating the element of variance and enabling high-precision clutch-torque control. The greater part of load hysteresis during operation, a factor that can reduce control characteristics, is seal friction. To reduce this, the type of hydraulic piston used was one that placed small-diameter plungers at two points, minimizing the impact of seal friction. This was first used as original technology in 2006 and subsequently became standard in HRF1.

4.5. Differential

The differential is one of the components showing the most progress toward compactness in the past 10 years, and according to data from a specialty manufacturer, differential assembly weights were just 6.1 kg in the 2004 specifications, a reduction of more than 50% from the 12.5 kg in 1998⁽²⁾. This progress is primarily the result of advancements in package technology and optimized safety factors. Since the differential is located higher than the vehicle's center of gravity, making it lighter is a very effective way of lowering the height of

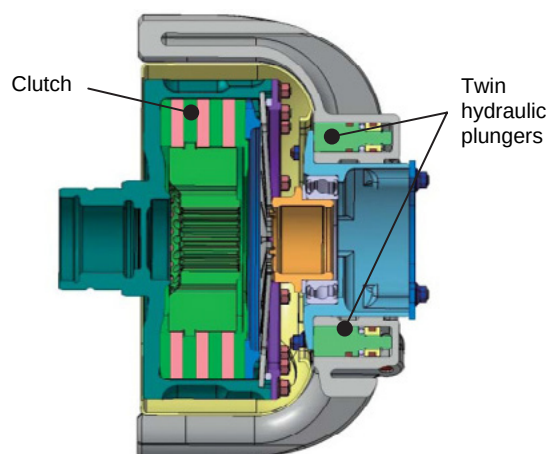


Fig. 5 Appearance of Direct Push Clutch (DPC)

the gravitational center. Reducing differential width, moreover, helps enhance aerodynamic performance and makes longer drive shafts possible, so the sweepback angle of the drive shaft is smaller, which enhances transmission efficiency. Differential mechanisms include a bevel gear set-type and planetary gear-type, but the latter is superior in terms of weight and total width. The HGT engineers also actively engaged in an effort to make differentials more compact, and developed a number of original technologies. This section introduces the Ultra Short Diff (USD), which used a unique mechanism to try to achieve a more compact differential. Figure 6 compares USD to RA108, the 2008 specification, in cross-section. Using a full-engagement double-pinion planetary has resulted in 20% less distance between centers and 14% lighter weight. By the end of 2008, the engineers had finished ascertaining performance, durability and reliability and were aiming to introduce the technology to racing in 2009.

4.6. Enhancement of Transmission Efficiency

The original key development goals were lighter weight, greater compactness and faster gear shifting, and Honda's unique development yielded results on these goals and enhanced competitiveness, so in 2006 the enhancement of transmission efficiency was addressed as a key issue. Table 1 gives the results of measuring transmission efficiency under maximum gearbox load at the time.

As is evident, most of the transmission loss came from the meshing of the gears. For that reason, the engineers added surface finishing to their research with the goal of reducing friction losses in gear engagement. Diamond-like carbon (DLC) coating yielded good results, and adding DLC coating to all ratio gears, the bevel gear and final gear made it possible to reduce transmission loss by 3.4 kW. On the subject of coating durability, at first there was an issue with the coating peeling off the bevel gear, which is subject to a particularly high level of contact surface pressure. This was solved by revising the materials and production methods, namely enhancing adhesiveness by reducing the underlying surface roughness and making the film finer, so this technology was used in part starting midway

Table 1 Classification of transmission losses (loaded)

Bearings	Gears	Seals	Churning	Pump
20%	62%	2%	14%	21%

through the 2007 racing season and on all gears starting with the 2008 season opening race.

The engineers additionally addressed how to reduce transmission losses through gearbox oil development. Generally speaking, lowering the oil's viscosity reduces churn resistance, but simultaneously reduces oil film thickness, which increases friction on tooth surfaces when in a boundary lubrication status and, as a result, lowers transmission efficiency. By reviewing various base oils, the engineers were able to address both churn resistance and friction loss on tooth surfaces, cutting transmission losses by 0.4 kW.

5. Conclusion

Although the third-era Formula One activities resulted in only one race victory, they also gave birth to seamless shifting and a number of other industry-first technologies, so Honda's engineers could at least take pride in such developments as they faced the closing of this era. As development began, it was marked by one failure after another, but the engineers learned many things and grew along the way. This is the prize won from participation in Formula One racing and will certainly be an asset for Honda into the future.

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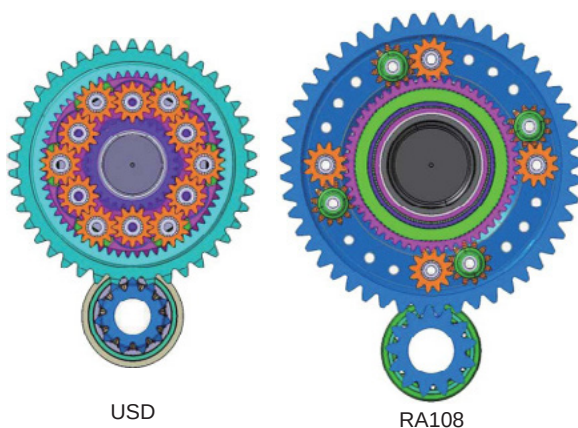


Fig. 6 Comparison between USD and RA108

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Atsushi MANO