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Development of Dual Clutch Transmission for Large Motorcycles

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ABSTRACT

Large motorcycles have a strong recreational aspect. Therefore, in addition to the sportiness that comes from the direct torque feel and the comfort that comes from the ease of operations, users demand improvements to fuel economy from the perspective of the environment and riding economics. In order to satisfy these needs, we have developed the world's first dual clutch transmission (hereinafter referred to as DCT) for motorcycles. In order to make the DCT more compact, we adopted a dual shaft construction for the main shaft, two hydraulic clutches arranged in-line, the basic structure of the gear shift mechanism carried over from a manual transmission (hereinafter referred to as MT) vehicle, a hydraulic circuit consolidated into the engine side cover, and shared use of engine oil for clutch actuation. Through these innovations, it became possible to carry over the die of the crankcase used on the MT vehicle as well as being able to load it onto the same frame as the MT vehicle. In order to achieve the smooth starts and gear shifts demanded of motorcycles, independent linear solenoid valves were positioned on each of the two clutches; this configuration makes it possible to control the clutch hydraulic pressure directly. At a standstill, no creep torque is applied. Then, by controlling the clutch hydraulic pressure rise characteristics immediately after starting launch controls, it is possible to start smoothly. Gear shifting by the two linear solenoid valves directly controlling hydraulic pressure makes it possible to control the clutch capacity of the driving side and the non-driving side with precision to realize smooth gear shifting with no drops in torque. A 5% improvement in fuel economy compared to the MT vehicle in WMTC mode was realized by optimizing the shift schedule.

INTRODUCTION

The most common type of automatic transmission (hereinafter referred to as AT) for motorcycles is the belt converter type equipped on scooters. With smooth starts and gear shift, it is loved by a wide range of users. At the same time, there are many users that prefer stepped transmissions with gear shift speeds that allow the user to enjoy sport driving and feel the torque being transmitted directly. Thus, we have fully automated a stepped transmission with a DCT system and built it onto a V4 engine (Fig. 1).

Fig. 1. External view of V4 engine with newly developed Dual Clutch Transmission

Table 1. Comparison of specifications of Manual Transmission and Dual Clutch Transmission

			Manual Transmission	Dual Clutch Transmission
Engine	Type		4-cylinder V-type	4-cylinder V-type
	Bore (mm)		81	81
	Stroke (mm)		60	60
	Displacement (cm^3)		1237	1237
Clutch	Type		Mechanical	Hydraulic
	Number		1	2
Transmission	Type		6-speed Manual	6-speed Manual + Automatic
	Ratio	Low	2.600	2.466
		2nd	1.736	1.789
		3rd	1.363	1.409
		4th	1.160	1.160
		5th	1.032	1.032
		6th	0.939	0.939
	Mainshaft no.		1	2
	Countershaft no.		1	1
	Axis length (mm)		75	75
Hydraulic	Oil capacity (L)		4	4.9
	Clutch control pressure (kPa)		—	900

DEVELOPMENT GOALS

A DCT is a technology that is already on the market in automobiles and ATVs (All-Terrain Vehicles) [1]. It is characterized as having the same direct torque feel and equivalent torque transmission efficiency as a MT, as it has the same elements to transmit torque, and it is widely known to have no drops in torque due to the controls that switch between the clutches at gear shifts. On the other hand, there are issues with these systems when performing starts with a hydraulic clutch. It is difficult to build a smooth start control system, and they require a more complicated construction than a MT. The aims of the development were thereby established as described below:

1. To make an AT that has sport performance and fuel economy performance equivalent to a MT vehicle.

2. To have smooth starts and gear shift characteristics suitable for motorcycles.

3. To be able to load the system onto the same frame as a MT vehicle and carry over the die of crankcase without making any changes to the basic positioning of the clutch, transmission shaft and gear shift mechanisms of a MT vehicle.

SYSTEM OVERVIEW

A comparison of the specifications of the MT and the DCT is shown in Table 1 [2]. A cross-sectional drawing is shown in Fig. 2. The engine torque is transmitted through the primary gear into the two clutches, then through the transmission and into the engine final shaft. The two clutches are connected to the main shaft individually with the gear trains of the #1 clutch connected to the odd-numbered gears (1st, 3rd and 5th) and the #2 clutch connected to the even-numbered gears (2nd, 4th and 6th). Gear shift methodology starts with the shift mechanism actuation to pre-shift the gear on the non-driven side clutch to a target gear position beforehand. The clutch hydraulic pressure is then switched over from the driven side to the non-driven side to change gears, then, the gear now on the non-driven side goes into the neutral position to complete the gear shift action. A time chart for shifts during starts and gear shifts is shown in Fig. 3. Switching between clutches is done by two linear solenoid valves that control the clutch hydraulic pressure individually. Switching between shift positions is done with a configuration that is automated by motor power using a shift mechanism that is the same as that of the MT vehicle. Gear shift modes are implemented to include an AT Mode that performs fully automatic shifting and a MT Mode that allows manual shifting of gears as commanded by the user through a shift UP/DOWN button located on the left grip. Starting is controlled automatically in both modes. In addition, there are two types of AT Mode: “D” designed for fuel-efficient riding, and “S” designed for sport riding.

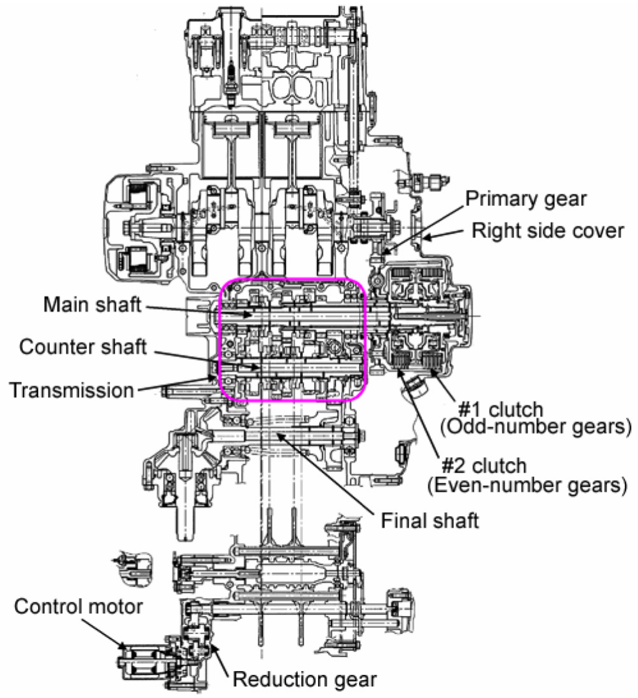

Fig. 2. Cross-sectional drawing of engine with Dual Clutch Transmission

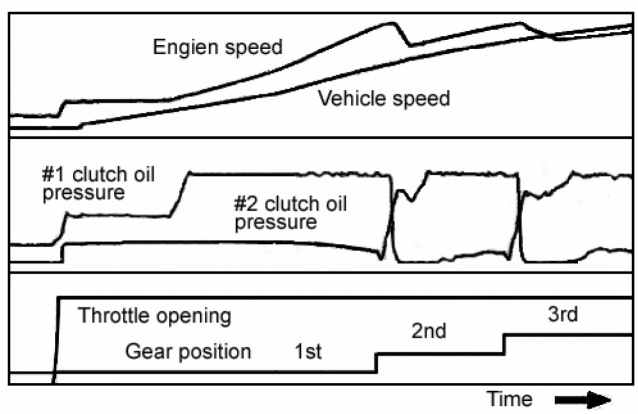

Fig. 3. Time chart for shifts during starts and gear shifts

CONSTRUCTION

LAYOUT

The die of the crankcase could be carried over by keeping a layout common to the MT vehicle for the basic positioning of the "clutch and gear shaft" and the "engine and transmission shaft", as well as the distance between the shafts. On the right side of the engine, the clutch and oil paths are positioned and consolidated with a side cover; on the left side is an electrically powered motor for automating the gear shift mechanism. With such a layout, it is possible to keep the same lateral center of gravity as the MT vehicle.

CLUTCH

A hydraulic piston system that uses the engine oil as its actuation oil was adopted for the clutch and a canceller chamber was set to cancel the centrifugal hydraulic pressure generated in the piston chamber. Hydraulic pressure is supplied to the clutch from a feed pipe on the right side cover of the engine, and goes through the inner main shaft. The main parts of the system are made of die cast aluminum, which reduces weight and improves the heat dissipation characteristics and actuation responsiveness. An in-line arrangement was adopted in order to retain commonality to the base MT vehicle for the two clutches and to equalize the inertia moment of the two clutches (Fig. 4). The system does not have a clutch exclusively for starting; the #1 clutch with odd-numbered gears is used as a starting clutch. Since the #1 clutch used for starting has more heat generated than the #2 clutch, the clutch plate thickness is thicker to raise its heating capacity.

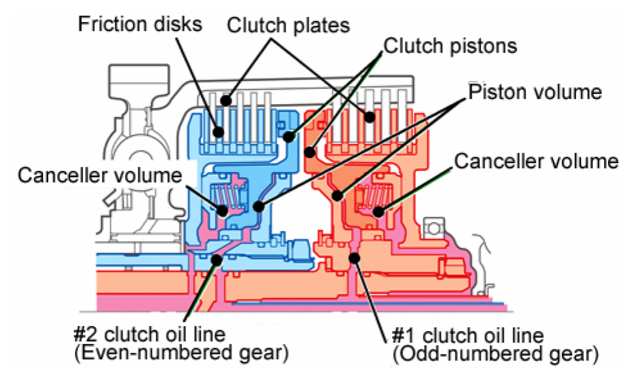

Fig. 4. Structure of Dual Clutch

TRANSMISSION AND GEAR SHIFT MECHANISM

A structural drawing of the transmission and gear shift mechanism is shown in Fig. 5. The transmission for the MT vehicle is set with close ratios on the 1st to 3rd gears to reduce gear shift noise from dog engagement during shifts. The basic construction of the gear shift mechanism for the MT vehicle was carried over to this system but in order to automate the gear shift motion performed by the rider's foot in the MT vehicle, the shift pedal was eliminated and an electrically powered motor and gear train were added. The dog transmission construction that actuates the drivable gear when moving the shift fork left/right by turning the shift drums is the same as the MT vehicle except that an angle sensor to detect drum phase was added. The shift drum has 12 positions (Table 2) and the non-driven side is put in standby during driving to improve fuel economy and reduce the differences in UP/DOWN shift speeds.

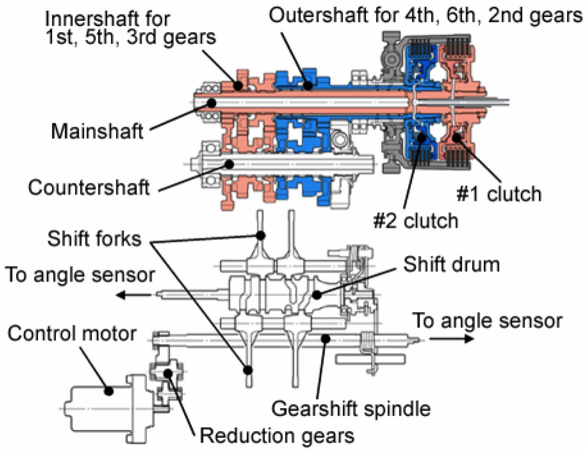

Fig. 5. Transmission and gearshift mechanism

Table 2. Shift drum position and gearshift conditions

Shift drum position #	Gearshift conditions	Engaged gear	
		Odd-numbered gears	Even-numbered gears
1	Neutral	N	N
2	Start , 1st	1	N
3	1st⇔2nd shift	1	2
4	2nd	N	2
5	2nd⇔3rd shift	3	2
6	3rd	3	N
7	3rd⇔4th shift	3	4
8	4th	N	4
9	4th⇔5th shift	5	4
10	5th	5	N
11	5th⇔6th shift	5	6
12	6th	N	6

HYDRAULIC CIRCUIT

A cross-sectional drawing of the oil pump is shown in Fig. 6. The pump was made more compact by adding an exclusive clutch control oil pump on the same shaft as the oil pump on the engine side. Additionally, the hydraulic circuit for clutch control is a high pressure circuit independent from the engine side to make the clutch more compact and reduce its weight. In order to perform precise hydraulic pressure control, there is a need to control fluctuations in the hydraulic pressure so the number of trochoid gear teeth was increased in order to reduce hydraulic pressure pulsation. In order to be able to control the hydraulic pressure independently on each of the two clutches, linear solenoid valves were positioned on the hydraulic circuits of two independent lines (Fig. 7). These hydraulic circuits were consolidated and positioned into the engine right side cover.

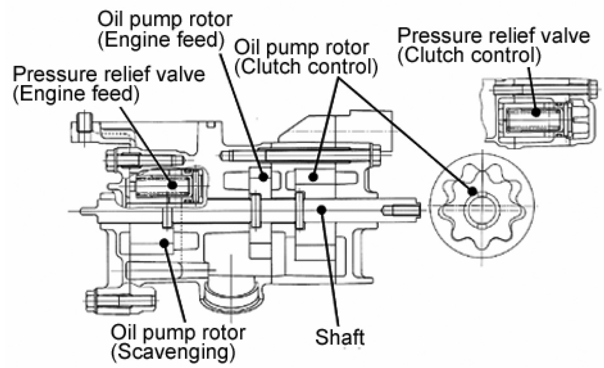

Fig. 6. Cross-sectional drawing of oil pump

OVERVIEW OF CONTROL SYSTEM

Figure 8 is a summary of the signals going in and out of the ECU. The rider's intent, as expressed in the throttle angle, each input switch, engine and vehicle speeds, and the DCT system operating condition, which is the rotational speed of each shaft, shift mechanism angle, oil temperature, and clutch hydraulic pressure are monitored and cross checked against the gear shift map while calculating the target gear position to output as motion signals for the clutch hydraulic pressure and gear shift mechanism.

STARTING AND GEAR SHIFT ACTUATION

DCT SYSTEM ACTUATION OIL

Due to the layout restrictions for motorcycles, it is necessary for the engine oil to also function as transmission lubrication oil; the DCT system also uses the engine oil as its actuation oil and lubrication oil. In general, changes in viscosity relative to temperature are greater for engine oil than for ATF (Automatic Transmission Fluid). Therefore, changing the response of the hydraulic control system in accordance with the change in viscosity generates considerable change in starting and gear shift feeling. In addition, different users prefer various types of oil. Therefore, the performance, demanded as a system, has to be flexible enough to cope with changes in the viscosity of the actuation oil.

Consequently, this system has adopted a hydraulic pressure feedback control using a hydraulic pressure sensor that constantly monitors the hydraulic pressure going into the clutch, as well as being equipped with logic to estimate the viscosity of oil by monitoring the hydraulic pressure rise response. The system is configured to flexibly cope with changes in oil temperature and viscosity by switching the feedback gain based on the estimated oil viscosity to minimize the effects that changes in viscosity have on starting and gear shift feeling as well as raise the response levels of the hydraulic control system.

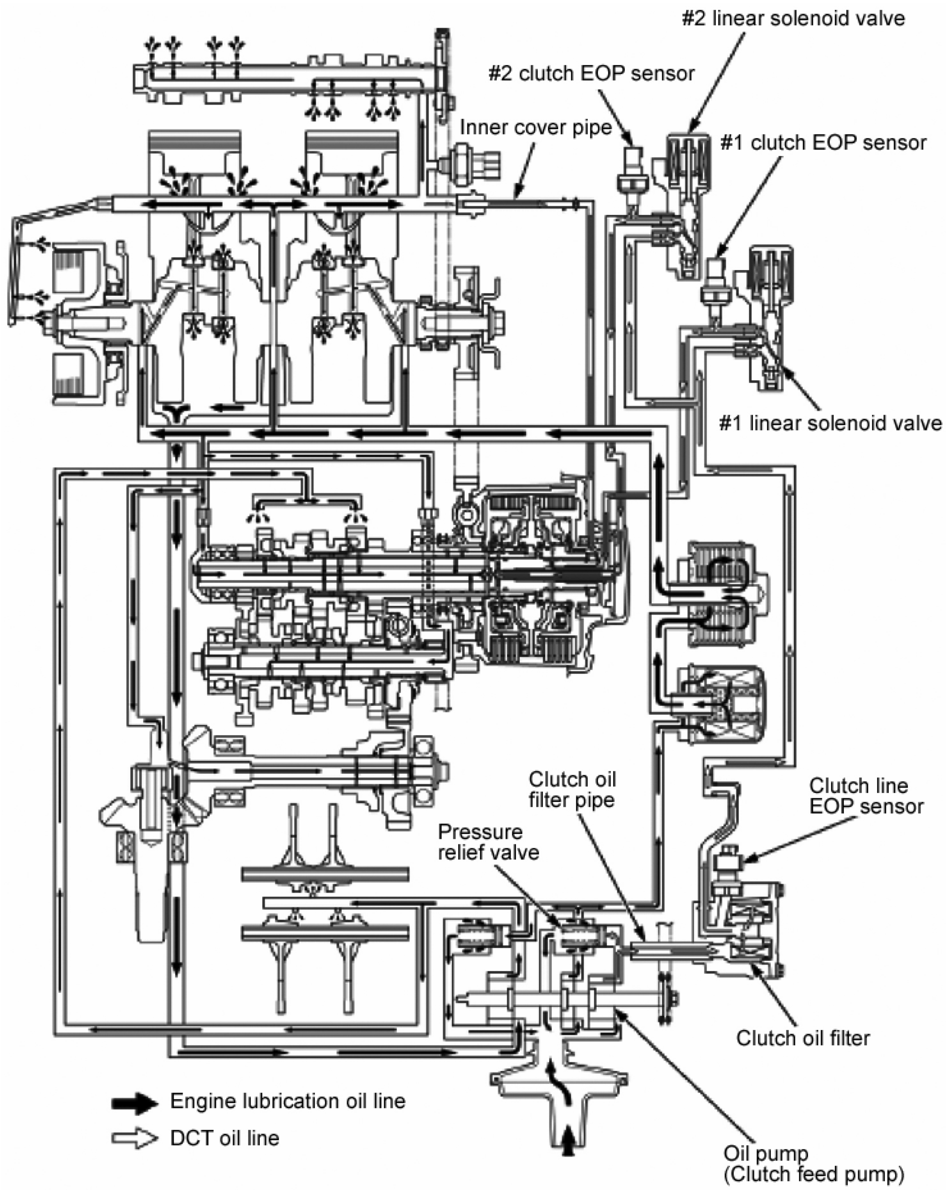

Fig. 7. Hydraulic circuit

STARTING ACTUATION

It has been common for AT systems on conventional motorcycles to be equipped with a dedicated start clutch such as a centrifugal start clutch, but on this system, independent linear solenoid valves are positioned on each of the two clutches to allow the clutch to be controlled with precision. Therefore, it is configured to use the gear shift clutch for the odd-numbered gears as the start clutch.

If the brakes are released with the vehicle in a stationary condition, a torque converter AT on an automobile moves the vehicle forward even if the accelerator is not applied. In other words, it has a creep condition. This is also true, in most cases, in vehicles that use control start clutches. On the other hand, automatic clutches such as are used in motorcycle centrifugal clutches generally have no creep and are structured to apply start torque to the transmission by opening up the throttle. This is quite significant for motorcycle ease of use as there is a need for the rider to support the motorcycle with his legs in a standstill condition. Therefore, it was necessary to structure the system to not transmit torque when the throttle is in a closed condition while at a standstill. However, if the controls on a hydraulically controlled start clutch are set to not provide creep torque in a standstill condition, then securing clutch capacity response immediately after a start launch would be difficult. The reason for this is that the clutch capacity is temporarily unstable, relative to the hydraulic pressure due to changes in the clutch piston chamber volume that occur until the clearances between the clutch plates and friction disk reach

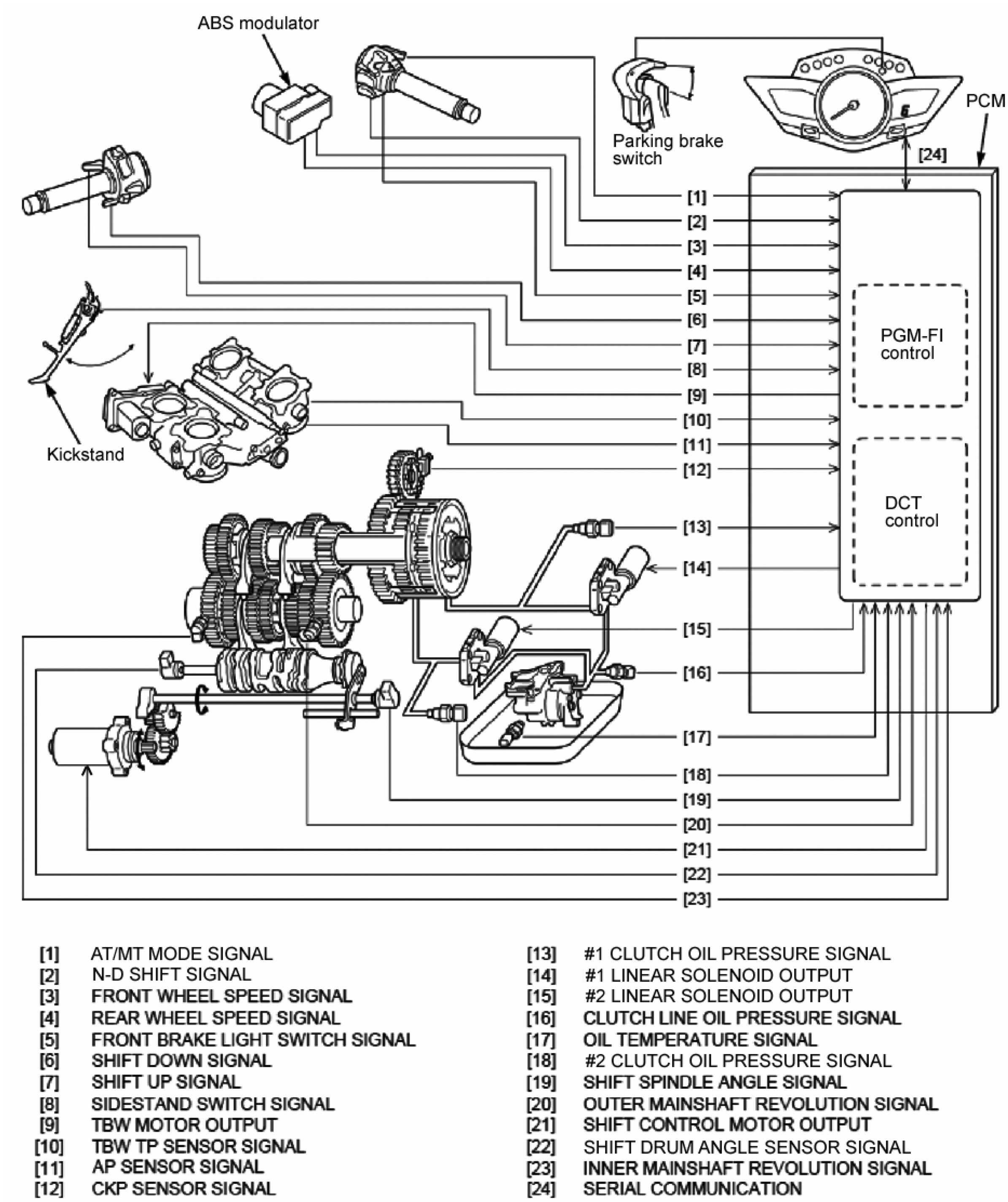

Fig. 8. Diagram of control system

"0", during the process of transferring from a "clutch open" condition to a "capacity transmitting" condition. Therefore, unless this condition is ended quickly, delays in capacity transmission could lead to engine revs and excessive capacity causing sudden acceleration.

In order to address this problem on this system, we focused on the time lag from opening the throttle until when the engine speed actually rises and set the controls to end clutch piston volume changes within that time. First, the clutch control target hydraulic pressure is raised to a level that generates a "week creep" when the system has detected that the throttle has opened. The throttle is already in an "open" condition at this point in time and can determine that the rider is intending to start moving. Therefore, having the motorcycle move forward in creep condition is not considered a problem for ease-of-use. Following this, there is an engine output response, and then the controls are set to provide target transmission torque to the clutch according to the throttle angle and engine speed after the engine speed rises (Fig. 9). By taking on this type of control sequence, complete disengagement of the clutch is realized while stationary while still securing sufficient capacity response before the engine speed rises, thereby making it possible to secure smooth start performance.

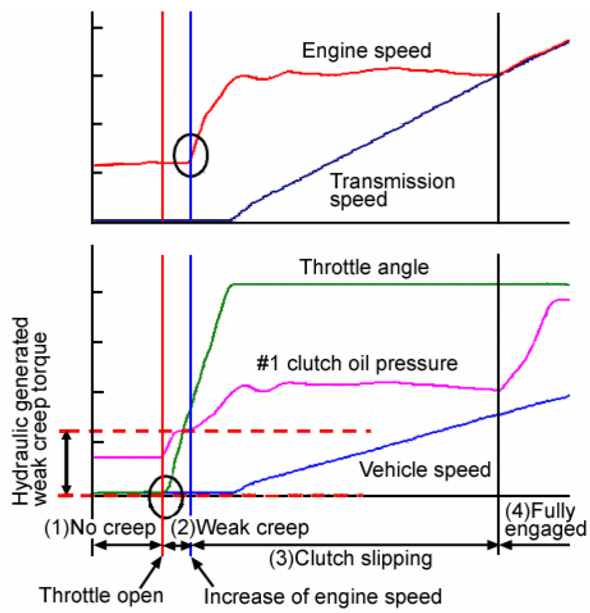

Fig. 9. Time chart during starting

GEAR SHIFT ACTUATION

In order for this system to carry over the die of crankcase used on the MT vehicle, it is necessary to use the same dog clutch type used on the MT vehicle as the torque transmitting and disengagement mechanism of the transmission. On the DCT, there is a need to connect the next gear beforehand, before the gear is shifted by switching the clutches triggered by changes in the actual torque; in other words, it is necessary to perform a preliminary shift. However, since a dog transmission is not equipped with a synchronizer unit like on automobile systems, engagement noise is generated from the sudden rotational speed fluctuation of the gear and shaft at the main part of the engagement during preliminary gear shifts. The same gear shift noise can also be found on a MT vehicle but the timing of the noise triggered on an AT vehicle has no relationship to rider operation. Therefore, it tends to be a more noticeable noise that would bother the rider compared to an AT vehicle, which is why reduction of this noise is important. On this system, the differences in the ratios of the low speed gears, where the pre-shift noise is noticeable, was therefore set smaller in comparison to the MT vehicle (Table 1), thereby reducing the energy absorbed by the transmission during preliminary gear shifts at low speeds. In addition, the drive system was optimized by performing special tuning on dampers for the DCT.

A motorcycle gear shift mechanism is a structure that engages and disengages gears by moving a shift fork with a shift drum. In using this construction as the base to build an AT system, there is no synchronizer mechanism which has the advantage of being able to shorten the pre-shift time. This system has a 250 ms time lag from the gear shift command till the actual torque fluctuation. Therefore, it has a gear shift response that does not feel unnatural.

At the same time, it is structurally impossible to shift by two gears or more in a single shift as realized on automotive DCTs, so especially for deceleration shifts with high consecutive shift requirements, it is important to secure a level of performance that can rapidly execute consecutive shifts.

The structure of the shift drum feed mechanism for this system was therefore changed from a shift drum rotation angle with a 60-degree feed configuration to a 30-degree feed configuration. This configuration switches gears every 30 degrees in this sequence: from “odd numbered gear engagement condition” to “odd/even numbered gear simultaneous engagement condition” to “even numbered gear engagement condition” to “odd/even numbered gear simultaneous engagement condition”. With this configuration, only the gear being used is engaged while driving and the gear on the side not being used goes into a “neutral condition”. In other words, we are able to realize an “N standby condition”. Once the gear shift command is sent out, the gear (on the side standing by) first engages, and then transfers to the “odd/even numbered gear simultaneous engagement condition”. For the drum feed mechanism, there is a need to return the shift spindle to the center after the dog has been engaged, but since the gear engagement condition is being monitored based on the shift drum angle sensor, it is possible to simultaneously perform a gear shift by switching clutches while returning the shift spindle. In addition, during a gear shift with a switch of the clutches, when the disengaged clutch that has become the non-driven clutch reaches a lowered hydraulic pressure condition, the dog of the released gear is moved and the released gear is put into a neutral condition. Consequently, at the point in time where the hydraulic gear shift sequence is finished, it is ready to accept the next gear shift. By linking this kind of shift feeding system control and hydraulic pressure controls, we were able to realize interval time targets for receiving consecutive gear shift requests of 500 ms or less (Fig. 10). The gearshift conditions are shown in Table 3. Gear shifting by two linear solenoid valves controlling the hydraulic pressure directly makes it possible to control the clutch capacity of the driving side and the non-driving side with precision to realize smooth gear shifts with no drops in torque.

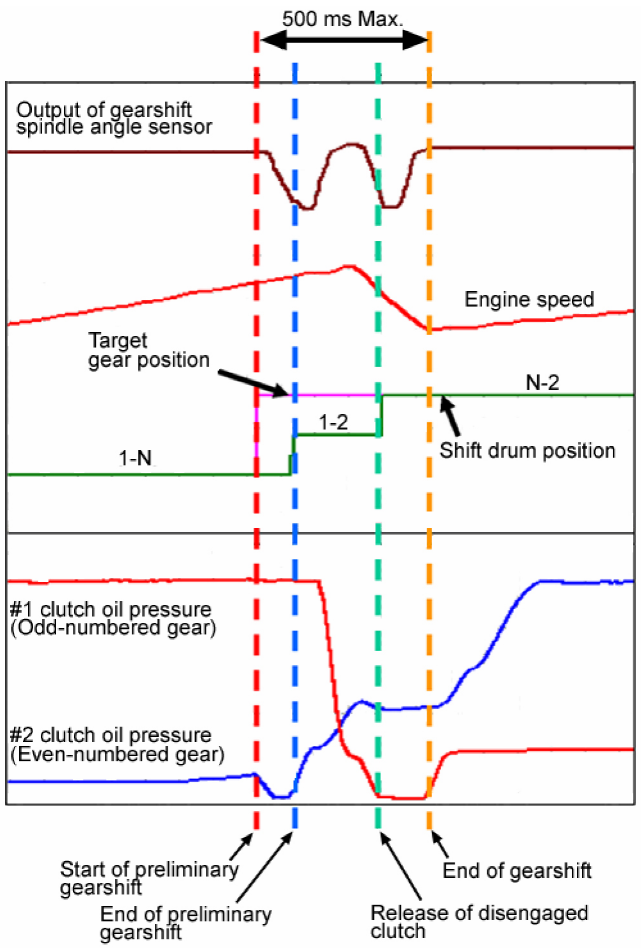

Fig. 10. Time chart of gearshift sequence

Table 3. Gearshift conditions for consecutive gearshift test

Gearshift conditions	Engaged Gears	
	Odd-numbered gears	Even-numbered gears
1st	1	N
1st ↔ 2nd shift	1	2
2nd	N	2

GEAR SHIFT SCHEDULE CONFIGURATION

The gear shift schedule configuration is equipped with three modes: D Mode, targeting city riding with priority placed on fuel economy; S Mode, targeting winding roads and sport riding, to be used in relatively high engine speed zones; and MT Mode, the rider can select the gear position at will by the UP/DOWN switch on the left handle.

A characteristic of motorcycles is that the body leans over to one side when cornering; because of this, it would be ideal to avoid changes in torque by triggering gear shifts when cornering whenever possible. Therefore, on top of controlling the clutch capacity with precision to secure the performance that sufficiently suppresses shift shock, there is a demand to not allow frequent inadvertent shifting when cornering. However, unlike automobiles that can detect cornering conditions relatively easily by looking at steering angle and rotational speed differences it is not easy to detect a cornering condition while riding. Consequently, for this system, we focused on the throttle operation patterns of the rider and introduced a logic that extrapolates that the body has started a cornering maneuver if a specific throttle operation pattern has taken place. We were able to effectively suppress gear shift actuation during cornering by adopting this cornering extrapolating logic.

In the MT Mode, since the rider's intent is input to the timing to start gear shifts, it is possible to adopt settings with an emphasis on gear shift timing compared to the emphasis on gear shift shock for the AT Mode (D and S Modes). Consequently, during down shifts, the engine speed is raised to match the rotational speed of the next gear to engage by a cooperative control with the TBW (Throttle by wire) system with both the odd and even numbered clutches in disengaged condition in the middle of a gear shift actuation. In other words, auto-blipping controls have been realized (Fig. 11). This blipping control makes it possible to significantly shorten the time to complete a gear shift compared to a shift in standard AT Mode and makes it possible to produce a sporty feel.

FUEL ECONOMY

The shift schedule was optimized by performing up-shifts early in D Mode (Fig. 12). As a result, The DCT vehicle was able to use a better fuel efficiency area on a fuel economy map (Fig. 13). This improved the DCT vehicle driving fuel economy by about 5% in WMTC mode compared to the MT vehicle.

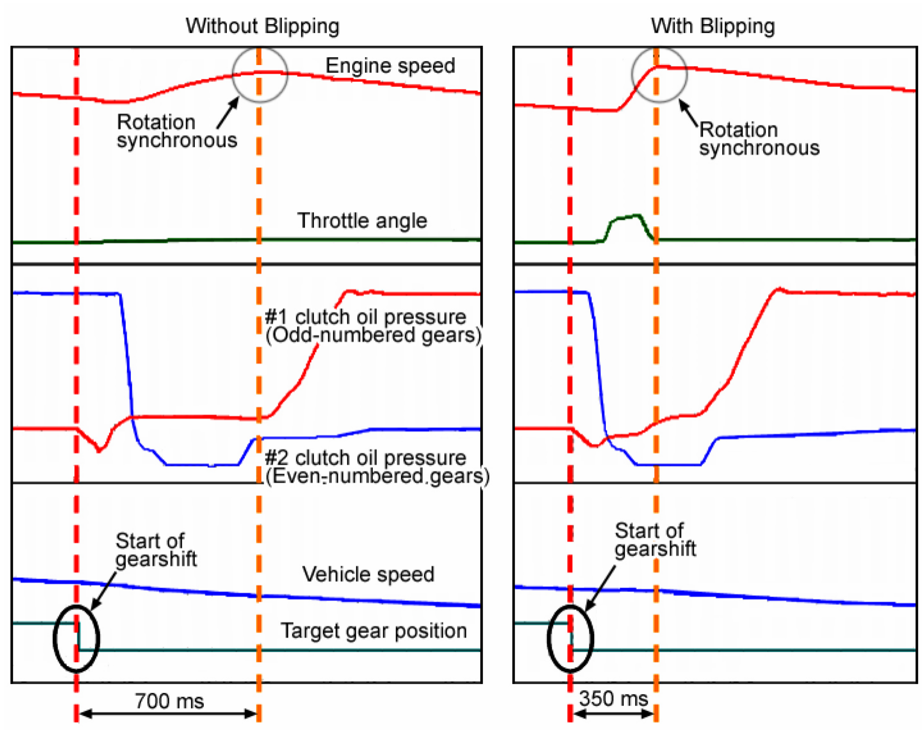

Fig. 11. Comparison of blipping effect (MT mode)

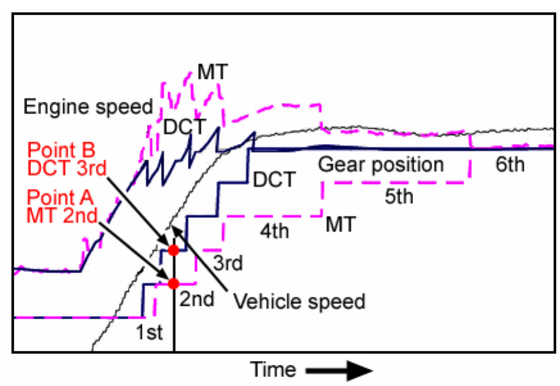

Fig. 12. Comparison of gearshift time chart

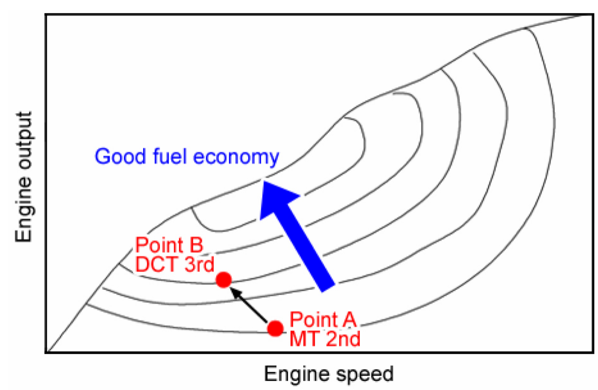

Fig. 13. Fuel economy map

CONCLUSIONS

1. The dual clutch transmission for motorcycles is fully automated, yet still realizes fuel economy improvements in addition to having the same sport riding traits as a MT vehicle.

2. The smooth start and gear shift performance demanded for motorcycles were achieved by individually controlling two independent linear solenoid valves.

3. We were able to develop a DCT that can be loaded onto the same frame as a MT as well as commonize the crankcase with a MT vehicle.

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