

Development of an Engine with a 3-speed Automatic Transmission for the “TRX650FA”

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ABSTRACT

The world's first engine with a torque converter has been developed for the paramount TRX650FA in Honda's utility oriented ATV (All Terrain Vehicle) line-up. A linear solenoid valve and a hydraulic clutch control the creep phenomenon at idling peculiar to the torque converter. The start-ability is equal to a wet automatic centrifugal clutch for conventional ATVs. A pleasant running condition, similar to an automobile, was achieved by employing an electronically controlled 3-speed automatic transmission. Assembly of the transmission and the engine using an existing production line was made possible because the lubrication systems of both the transmission and the engine were designed in common. A substantial weight reduction was achieved by optimizing the design of each part.

1. Introduction

The ATV market centered predominately in America is experiencing an accelerated trend toward large vehicle displacement and automated features in order to provide greater comfort and running performance. In 2000, Honda released its TRX500FA featuring a hydraulic mechanical CVT⁽¹⁾. In achieving its line-up of automatic models, it was necessary to design models with a larger vehicle displacement. In addition, weight reduction is highly desirable for improving maneuverability for off road driving conditions required by ATVs. In addition to achieving a larger engine displacement configuration and improved specifications including 4-wheel independent suspension and a selectable 2-wheel/4-wheel drive mechanism, the TRX650FA has also retained the superior features and weight of the TRX500FA. Figure 1 shows the exterior view of the TRX650FA. In addition to achieving a lighter weight engine, and to provide the appropriate torque to provide the standard of running stability required by ATVs, a 3-speed automatic transmission with an in-built ATV-specific micro torque converter was developed.

2. Development Goals

This vehicle has achieved a balance of riding comfort and running stability, at higher performance levels, suitable to the top fleet model series. Also this new model focuses on ease of handling for the leisure driver while incorporating a revolutionary design concept.

The engine, together with its uniquely configured torque converter, provides a smooth and powerful starting level of performance highly suited to such large displacement vehicles. A 3-speed automatic transmission was also adopted to provide the novice ATV driver with ease of handling and a sporty gearshift feeling similar to a manual transmission.

The torque converter has a unique output torque character which delivers a powerful starting through its effect of torque amplitude. Accordingly, as the vehicle increases in speed, the rate of torque converter slippage is minimized to provide a reduced torque output. This serves to stabilize the tire grip over loose off-road or dirt conditions. The torque output provides an enjoyable drive sensation during times when the throttle opening is frequently adjusted to provide a stable ride over uneven off-road conditions. The basic engine

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configuration employs a crankshaft design which sits longitudinally to the vehicle's traveling direction and is unique to Honda 4-wheel drive ATVs. Adopting this configuration in which the crankshaft and final output axial are set parallel to one another, has achieved an effective means of eliminating the necessity for a bevel gear for the engine's final reduction mechanism. This has been effective in promoting weight reduction.

3. Engine Overview

The layout of the main engine parts has been designed with due consideration to assembly on the manufacturing line and employs a similar configuration to that used in the conventional ATV engines. The generator and starter motor have been positioned on the rear part of the engine, and the torque converter, oil pump and water pump etc. have been positioned on the forward part of the engine. Oil beneath the crankshaft is scavenged by the oil pump. This configuration lowers the oil surface and the positioning of the crankshaft center. This design has contributed to reducing the size of the forward projecting configuration to approximate that of the TRX500FA. Figure 2 shows an external cutaway model view of the TRX650FA engine.



Fig. 1 External view of TRX650FA

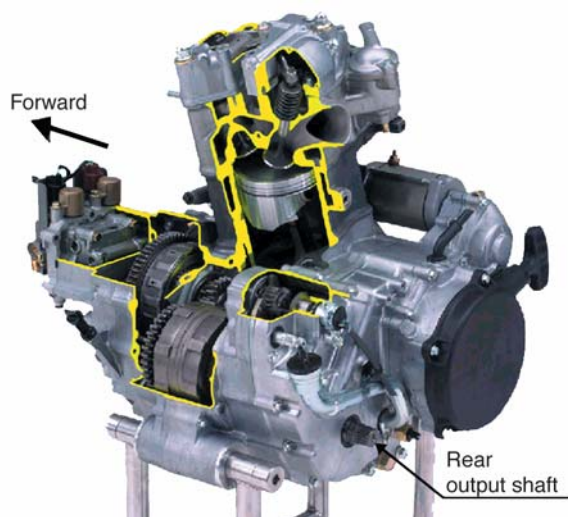


Fig. 2 Cutaway model of TRX650FA engine

Parts used in the XR650R motorcycle were taken into consideration to achieve a 648 cm³ displacement with a bore × stroke setting of 100 mm × 82.6 mm. The maximum output is 27.3 kW/5500 r/min and the maximum torque is 49.9 Nm/4500 r/min to emphasize a low speed torque that matches the torque converter specifications and provides ease of handling. Figure 3 provides an illustration of the engine performance curve and Table 1 lists the main specifications.

4. Torque Converter

4.1. Basic Specifications

In typical automobiles, the torque converter is positioned in a dry chamber located between the engine and transmission. The input and output positions on the torque converter are set at opposite ends of the main torque converter unit.

As shown in Fig. 4, instead of the automatic centrifugal clutch found in conventional ATVs, the torque converter adopted in TRX650FA is positioned on the crankshaft.

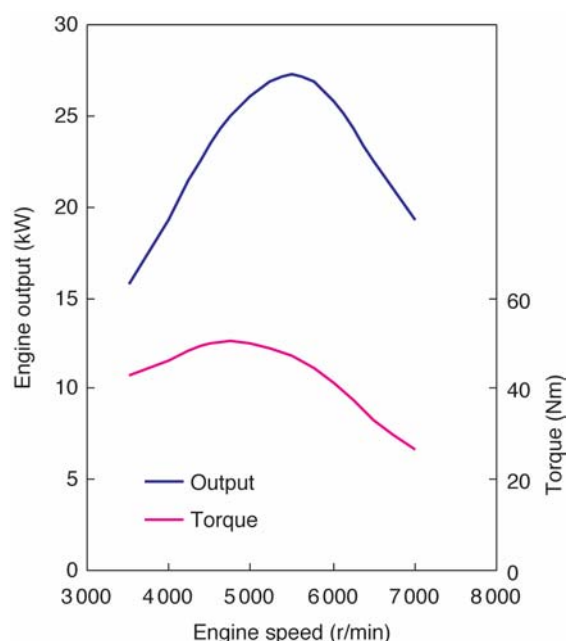


Fig. 3 Engine performance curve

Table 1 Specifications of engine

Engine type	Liquid cooled 4-stroke single cylinder	
Displacement	(cm ³)	648
Bore × Stroke	(mm)	100 × 82.6
Compression ratio		9.2 : 1
Valve layout		OHV 4-valve
Max. output	(kW/r/min)	27.3/5 500
Max. torque	(Nm/r/min)	49.9/4 500
Engine mass	(kg)	59.8
Torque converter		3-element, 2-phase
Creep control system		Direct hydraulic controlled system by linear-solenoid
Transmission type		Constant-mesh type 3-speed automatic

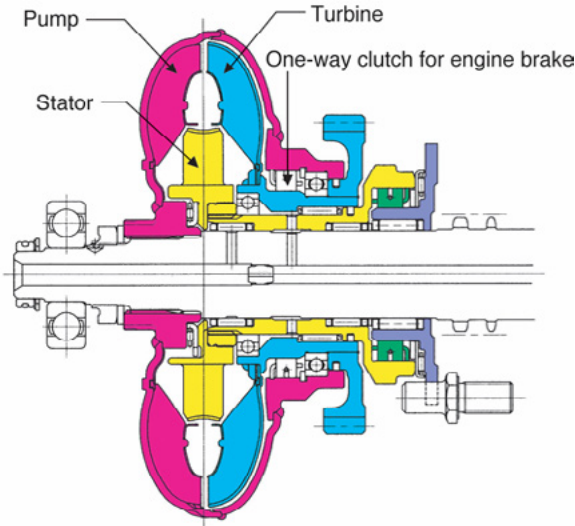


Fig. 4 Structure of torque converter

Therefore, the input and output positions of the torque converter have been positioned on the same side. Additionally, because the torque converter is positioned in the wet chamber inside the crankcase, the seals have been designed with a simple finish to allow slight oil leaking to lubricate the shaft bearing. On the other hand, the shaft bearing has been designed with a complex dual capability to accommodate input-output functionality. As shown in Fig. 5, the torque converter adopts a typical 3-element, 2-phase type configuration while the pump is fixed to the crankshaft with a nut and the primary drive gear is welded to the turbine. The stator rotation is transferred to the stator one-way clutch via the inner shaft. When coupling occurs, the stator normally rotates freely. When the unit stalls, the reverse stator rotation sends a reactive force via the inner collar to the lock pin, which is bolted to the crankcase, causing the torque to increase. Table 2 lists the main torque converter specifications and Fig. 6 illustrates the performance curve of the torque converter. Because ATVs are significantly lighter than typical automobiles, they do not require a large torque ratio. The maximum drive power and maximum drive force from the low pressure tires required for ATVs, are set to a



Fig. 5 Cutaway model of torque converter

Table 2 Specification of torque converter

Hydraulic diameter	(mm)	146.5
Number of blades	Impeller	28
	Turbine	23
	Stator	15
Torque converter dry mass	(kg)	3.0
Max. torque	(Nm/r/min)	49.9/4500
Vehicle dry mass	(kg)	273
Torque mass ratio	(kg/Nm)	5.5
Used oil type		Engine oil

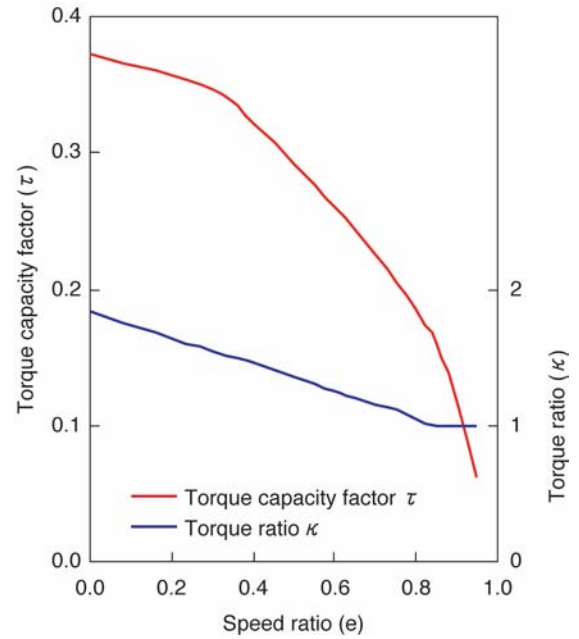


Fig. 6 Torque converter performance curve

low ratio with the torque ratio $\kappa = 1.8$ for a speed ratio $\epsilon = 0$. A balanced engine torque has been achieved by setting the torque capacity factor τ to 0.38 for a speed ratio $\epsilon = 0$.

When ATVs are running over uneven off-road conditions there is a large variation in the running resistance that affects the ability to keep a constant cruising speed and this could cause a throttle open-close operation. To reduce gear-shifting frequency and promote a smooth running performance under such running conditions, the torque capacity factor curve is lowered slightly to the right in relation to the increased speed ratio. Figure 7 illustrates the variation in the turbine torque performance curve in respect to the engine speed. As the torque amplitude decreases, the engine speed and vehicle speed increase slightly to yield a smoother acceleration.

4.2. Compact Light Weight Design

In appraising the drivability of a vehicle, both the stationary and transitional characteristics must be taken into consideration. To find the ideal torus for the previously described setting conditions, a 3-dimensional CFD⁽²⁾ was conducted. In addition, three different torque converters were made according to the specifications listed in Table 3 and illustrated in the capacity factor curves shown in Fig. 8. Calculations and fine adjustment tuning was conducted repeatedly to achieve the particular specifications for this

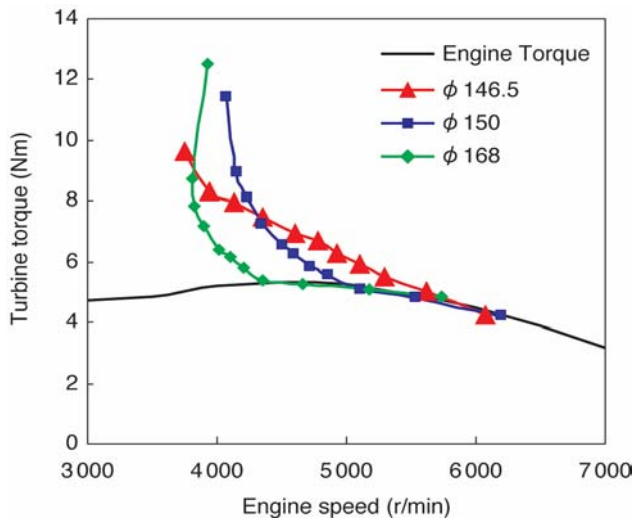


Fig. 7 Turbine torque performance curve

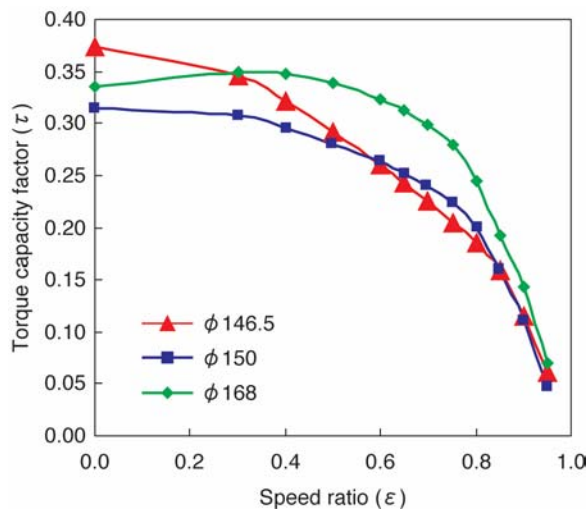


Fig. 8 Torque capacity factor curve

Table 3 Comparison of torque converter size

Hydraulic diameter (mm)		146.5	150	168
Number of blades	Impeller	28	23	23
	Turbine	23	21	21
	Stator	15	11	11
Torque converter dry mass (kg)		3.0	3.3	4.0

model unit. The hydraulic diameter was set at 146.5 mm to achieve the targeted settings.

A blade thickness of 0.5 mm was attempted to improve driving efficiency and facilitate weight reduction. A balance of strength, pressing, welding, wax adhesion, etc. were utilized in the manufacturing to achieve the most suitable levels of thickness for each part. This has resulted in a 25% reduction in weight compared with the initial specifications.

4.3. One-way Clutch for the Engine Brake

The performance of the engine brake according to the gear ratio is important to promote easy handling for ATVs. Typical hydraulic controlled lock-up mechanisms have a more complex configuration for supplying oil pressure to the

control system and torque converter. Also, the actuating responsiveness of a hydraulic clutch is instrumental in facilitating the engine brake just as the throttle is closed. The currently developed system embodies a simple configuration which ensures a reliable performance and has adopted a mechanical one-way clutch adapted for the engine braking system and is built into the torque converter. The one-way clutch has been adopted to the automatic centrifugal transmitting clutch in most ATV engine brakes for its highly reliable performance. Figure 9 shows an external view of the one-way clutch.

4.4 Integrated Lubrication System

Oil used for operating the torque converter is supplied from inside the crankshaft and also serves to lubricate the connecting rod bearing. The quantity of oil drawn from the oil pump is regulated as it passes the orifices positioned along the upper side passage of the crankshaft and the oil pressure is also reduced. The lubricated passages leading from the inside of the crankshaft are divided into separate passages that lead to the torque converter and the connecting rod. The amount of oil flow is also distributed as it passes over the respective orifices. Oil expelled from the torque converter is returned to the crankshaft and in combination with the oil separated by the orifices, is supplied in total to the connecting rod bearing. Oil supplied to the connecting rod bearing is also used to lubricate the support bearings for the pistons and crankshaft branches. After the oil accumulates in the oil pond located beneath the crankshaft, it is scavenged to the oil tank by the exclusive oil pump. This configurational design has enabled a simple lubrication passage to the torque converter while providing a means of effective oil scavenging.

5. Creep Control System

5.1. Structural Overview

Creep phenomenon promotes smooth drive torque transition as the vehicle starts and is effective in improving torque output as the vehicle starts on loose off-road surfaces and on inclining off-road conditions. In typical automobiles, the creep phenomenon is peculiar to torque converters. Mechanical automatic centrifugal clutches are typically used



Fig. 9 External view of one-way clutch

as the drive clutch on ATVs. When the engine is idling, the vehicle does not move by drag torque of the clutch.

Creep phenomenon is effective for drive performance. However, to ensure a similar degree of handling performance as other ATVs on the market, a creep control system was developed to eliminate creep when the vehicle is in the stationary idling position. Figure 10 illustrates a structural diagram of the transmission. The TRX650FA incorporates three hydraulic clutches for the 3-speed automatic shifting. When shifting gears, the electronic controller switches the hydraulic circuit to the clutch and transfers the drive force to each gear setting. When the engine is idling and the vehicle is stationary, just as when the vehicle is in neutral position, the control system shuts the hydraulic pressure to the clutches to prevent any creep from occurring.

5.2. System Overview

As shown in Fig. 11, the hydraulic circuit including the gearshift control system, is configured with the linear solenoid valve set to the upper aspect of the hydraulic switching valves for gear-shifting. The parameters for controlling the vehicle speed, the degree of throttle opening, the engine speed, oil temperature, etc. gradually generate the hydraulic pressure as required. To control on and off of creep without any sense of irregularity, it is essential to improve the responsiveness of the clutch engagement in respect to the engine speed. To enable this, the hydraulic circuit has been set to as short as possible a length leading up to the low clutch. A highly responsive free-ball type check valve has been adopted to the clutch. A minimal amount of hydraulic standby is supplied from the linear solenoid valve and fills the circuit to the low clutch with oil. Furthermore, to stop creep at low oil temperatures and eliminate any sensation of connection as the oil temperature changes, the standby hydraulic pressure is controlled by oil temperature. This has enabled responsiveness to intermittently occurring creep and a characteristic connection feeling equivalent to an automatic centrifugal clutch. Figure 12 shows the creep engage performance curve.

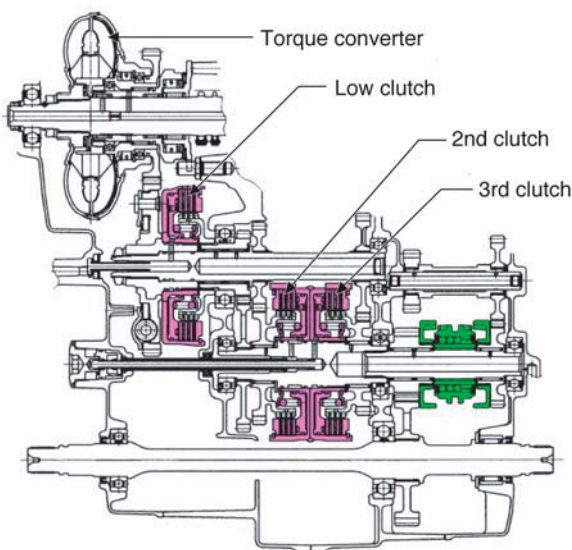


Fig. 10 Structure of transmission

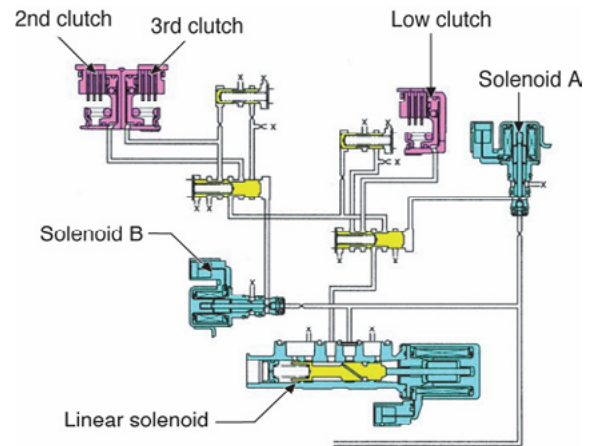


Fig. 11 Structure of hydraulic circuit

6. Automatic Gearshift System

6.1. Basic Configuration and Structure

The newly developed transmission comprises four elements engaged, three clutches, and a mechanical gear-shifter. In forward gear, the respective clutches engage with three speeds each to transfer the drive force. In reverse gear, the low clutch and mechanical gear-shifter are engaged in the ‘R’ position. Table 4 lists the relevant gear levels and clutch operations. Convex dogs and dogs holes are used to mechanically switch drive ranges between the ‘N’ neutral, ‘D’ drive and ‘R’ reverse gears. A switching mechanism located on the lower side of the clutch is operated via the control cable leading from the column lever, which is situated close to the driver’s hands. As there is no creep occurrence before and after the switching and all of the clutch hydraulic pressure is shut by the linear solenoid valve, a smooth switching range is enabled.

6.2. Overview of Gearshift Control System

The gearshift control hydraulic circuit is basically the same as that employed in typical automobiles but has been further simplified for a more balanced adaptation required by ATV vehicles. Low pressure tires unique to ATVs are highly suited to drivability over uneven off-road conditions and

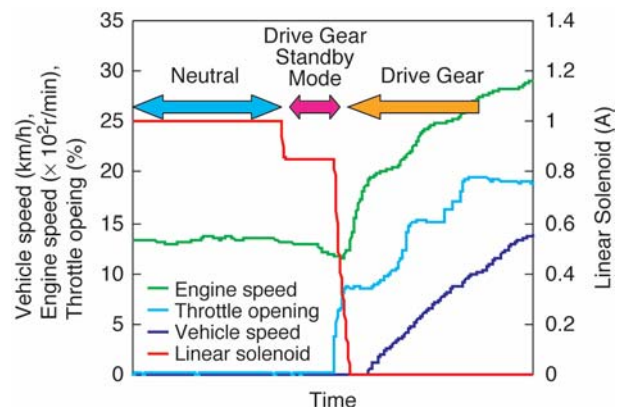


Fig. 12 Creep engage performance curve

contribute significantly to softening the shock from gearshift changing. Consequentially, the need for parts such as the accumulator, which is used to control hydraulic changes during clutch switching and thereby reduces the gear-shifting shock, has been reduced. Gear-shifting acts as a controller along with the two on-off solenoid valves. Table 5 lists the on-off solenoid valve application controls according to the gear-shifting. When a system malfunction occurs, power to the solenoids is shut by the relay causing the A and B solenoids to shut off and sets the gear position to 2nd. In case the solenoid drive circuit is in an unknown condition, the circuit is configured so that solenoid A is set to 'Off' when solenoid B is 'ON'. This configuration prevents a jumping gearshift from 3rd gear to low gear. Figure 13 illustrates the solenoid circuit diagram.

Table 4 Operating conditions

Elements engaged	Clutch			Mechanical shifter
Actual gear	Low	2nd	3rd	D/N/R
Neutral				N
Low	○			D
2nd		○		D
3rd			○	D
Reverse	○			R

Table 5 Solenoid application and actual gear

Actual gear	On-Off Solenoid	
	A	B
Low	On	Off
2nd	Off	Off
3rd	Off	On

6.3. Hydraulic Control Valve Body Unit

The valve body unit which controls gear-shifting is best to be assembled in a clean room while preserving quality control to prevent any operational damage that may be caused by contaminants from the hydraulic switching spool valve. The engine is manufactured on an existing assembly line which is not sufficient to manage the introduction of contaminants on the production line. For this reason, the linear solenoid valve, on-off solenoid valve, and the gear spool valves have all been incorporated into a single unit. This has then been assembled inside a clean room to ensure functional integrity of the unit. The valve body unit and the oil filter element have been assembled within the clean room on the front cover which forms the central high pressure oil passage to prevent the introduction of any contaminants to the upper side passage of the valve body.

Service maintenance has also been taken into consideration in the design of the valve body unit to enable easy removal from the outer engine. Figure 14 shows an external view of the valve body.

6.4. Hydraulic Clutch

The basic configuration of the hydraulic clutch incorporates successfully applied elements of the automatic transmission used in typical automobiles. The pistons have been constructed of aluminum die-cast, which contributes to weight reduction. To reduce the load build-up to the pistons, the maximum level of hydraulics being used and the return spring load have been reduced. Also, the pistons have been set to the same space as that for accommodating steel pistons to achieve a 0.6 kg weight reduction for the three clutches. Figure 15 shows an external view of the clutch piston. Figure 16 illustrates a comparative structural diagram of a conventional steel piston and an aluminum piston.

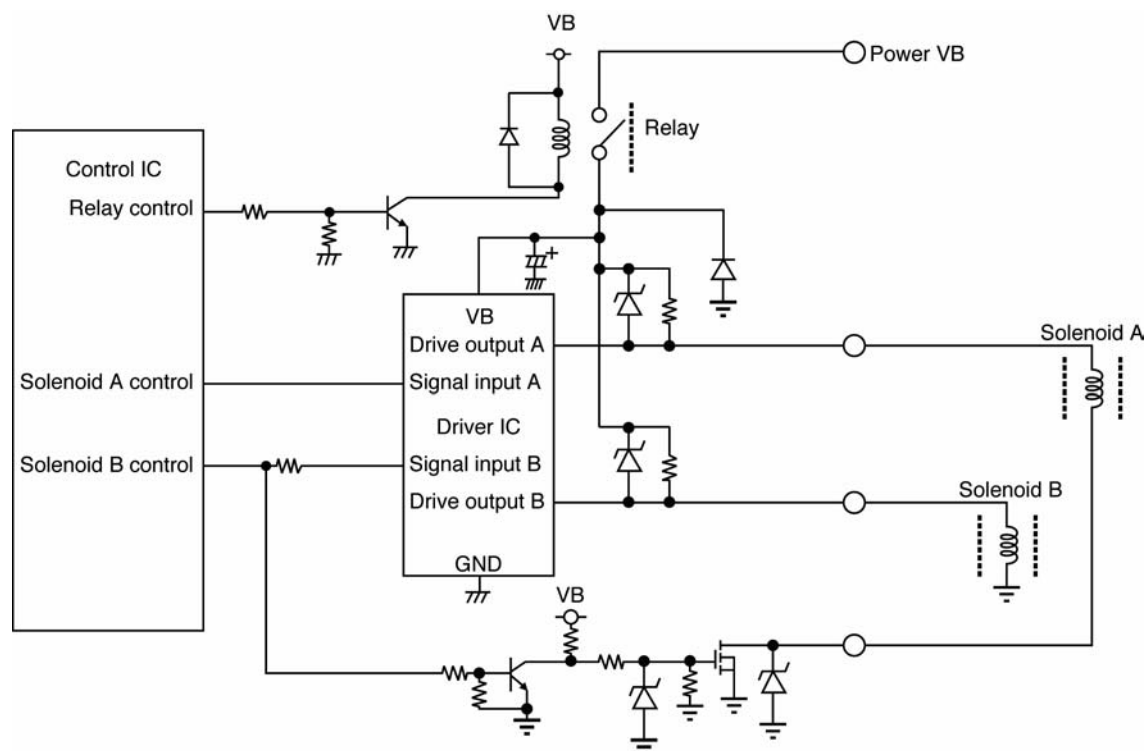


Fig. 13 Solenoid circuit



Fig. 14 External view of the valve body

The check valve emphasizes responsiveness during intermittent creep occurrence and has adopted a free-ball type configuration. In automobiles, in order to reduce the degree of gearshift shock it is necessary to provide greater clutch control. This has been achieved by changing from the free-ball type check valve to a leaf-valve type to decrease the centrifugal pressure. Also, a centrifugal hydraulic cancellation type⁽³⁾ has been adopted to improve the functionality.

As previously described, low pressure tires are invaluable in reducing the degree of gearshift shock in ATVs. Particularly, when running at high speeds, the influences from vehicular acceleration are greater than the gearshift shock, which presented no particular concern in the product profile. At the time of starting the vehicle, on the other hand, the responsiveness during creep engagement is readily transmitted to the rider due to enhanced tire gripping and less vehicle acceleration. To emphasize this responsiveness at low speeds, a free-ball type check valve has been adopted. Figure 17 shows the acceleration character at gear-shifting.

7. Gear-shifting Control System

7.1. Control Unit

The motor drive gearshift⁽⁴⁾ specifications and basic ECU in mass produced ATVs have been combined and a slave unit has been added for creep and automatic gearshift control. By conducting interactive transmissions between the ECU and slave unit, greater extension flexibility to exclusive parts and a more compact and lightweight configuration design have been achieved.

7.2. Slip Determination

In running over uneven off-road conditions, the variance in the throttle opening increases to stabilize the vehicle positioning. Furthermore, if tire slippage occurs at too great of a frequency this may cause the wheels to lock on loose off-road conditions. Under such conditions, the difference in vehicle speed and speed sensor detection value increases causing up/down gear-shifting. This shifting might contribute to some decrease of the running performance. To accurately determine the vehicular speed and achieve accurate gear-shifting, the vehicle speed acceleration rate has been set according to a time variable setting. This enables accurate



Fig. 15 External view of clutch piston

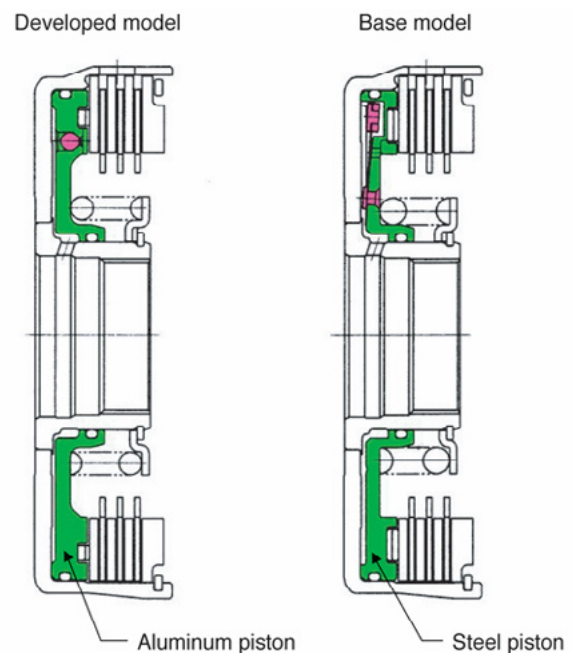


Fig. 16 Structure of clutch piston

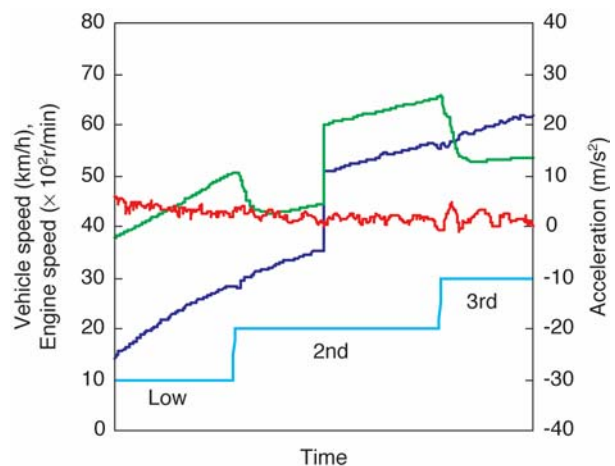


Fig. 17 Acceleration character at shifting

speed increase and decrease readings. Sharp increases in vehicle speed detection values determine tire slipping while drastic decreases in the vehicle speed detection value determine wheel locking. Then, control to set the gear to the current level is implemented to prevent unwanted gear-shifting.

7.3. Cornering Mode

In running conditions ranging from where the throttle opening is large to a cornering scenario in which the throttle closes completely, sometimes the vehicle is shifting up in accordance with the gearshift map. One way to help prevent this from occurring is to determine the running condition and fix the degree of gear-shifting. For ATVs running over uneven off-road conditions, it is quite difficult to determine the degree of off-road surface variance. By focusing on the throttle opening rate, a control has been added for fixing the gearshift level when a sudden throttle closure occurs. In addition, when the throttle opening is less than 20%, the gearshift point is transferred to the higher vehicle speed range.

This helps prevent an unwanted gear-shifting up when the throttle closes. Even if a low throttle opening is maintained, it also helps prevent unwanted shifting up. Therefore, a constant running speed is stabilized at a minimal load.

7.4. Descent Mode

For travelling on a descending off-road conditions, a customized gearshift map for enacting early downshifting in response to brake signaling is provided to increase engine braking and enable acceleration after deceleration. Figure 18 shows the performance curve of the shift control map.

8. Summary

The newly developed TRX650FA engine has adopted numerous new mechanisms to achieve the following.

- (1) An engine weight of 59.8 kg with a maximum output power of 27.3 kW/5,500 r/min and a torque of 49.9 Nm/4500 r/min.
- (2) A similar degree of engagement as conventional automatic centrifugal clutches by employing a creep control system that uses a linear solenoid valve.

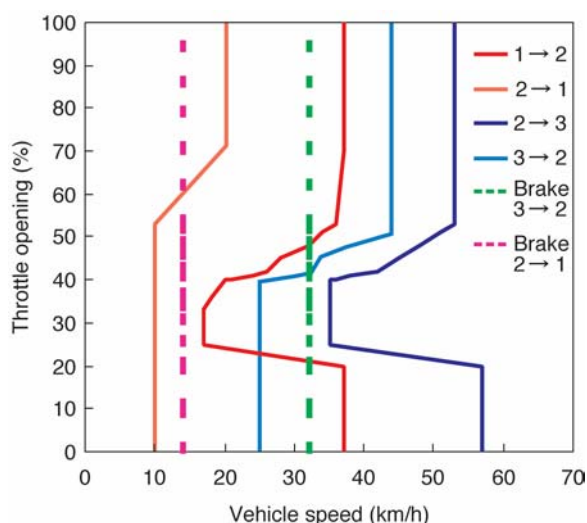


Fig. 18 Shift control performance curve

- (3) Accurate recognition of slip conditions by calculating the rate of change in throttle opening and vehicular speed. Have achieved a gearshift control characteristic highly suited to ATV running performance.
- (4) A gearshift control characteristic highly suited to ATV running performance.

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