

Development of SH-AWD (Super Handling-All Wheel Drive) System

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ABSTRACT

In a world first, Honda has developed the SH-AWD (Super Handling-All Wheel Drive) system, enabling complete control of torque distribution to any wheel, front or rear, left or right.

A direct electromagnetic clutch in which solenoid attraction acts directly on the clutch was newly developed to enable the system to be realized. In addition, a 2-speed shift unit was developed to adjust differential revolutions in the clutch in order to enable the system to exert control under all conditions.

The use of this system in a vehicle provided incredible neutral steering and high vehicle stability by direct control of turning yaw moment through differential distribution of torque to the right and left wheels. The vehicle also experienced enhanced cornering limit performance by equalization of the load ratio between the wheels through differential distribution of torque to all four wheels.

1. Introduction

Recently, along with the increasingly high output of vehicles, there has arisen a tendency for a four-wheel drive train to be adopted instead of a two-wheel drive train. Conventional four-wheel drive trains have been devised in a variety of forms and put into practical application. Generally, a four-wheel drive train that places emphasis on vehicle maneuverability has low traction capability. Additionally, a four-wheel drive train that emphasizes traction is difficult to enhance cornering performance. In order to solve these issues, systems that electronically distribute the drive force between the front and rear wheels, and also systems that distribute the drive force between the left and right rear wheels, have been devised and put into practical application⁽¹⁾. However, there was no known system that enabled both the front and rear wheel drive force and the left and right rear wheel drive force to be freely varied.

The results of analysis by β -Yaw Moment Diagram⁽²⁾ indicated that direct control of yaw moment utilizing the difference in the lateral drive forces was effective for enhancing cornering performance and stability. This was verified in 1997 by means of an Active Torque Transfer System (ATTS)⁽³⁾ mounted in a vehicle.

This paper describes the development of the SH-AWD system, the world's first four-wheel drive system that freely

controls both the left to right distribution and front to rear drive forces, in order to increase the cornering performance and stability to the maximum limit. This system, which is based on the high drive performance of the four-wheel drive vehicle, employs direct control of yaw moment utilizing the difference in the left and right drive forces, in order to help minimize changes in the behavior of the vehicle when the accelerator pedal is pressed during cornering. In addition, the front and rear drive forces are distributed according to the engine torque and longitudinal acceleration, thus reducing tire slip when the accelerator is abruptly depressed.

A study was carried out with a view to adopt this system in the new LEGEND/ACURA RL, that was announced in the autumn of this year, to help reduce the necessity of carefully depressing the accelerator pedal and correcting the steering according to driving situations and road conditions, thereby reducing the burden on the driver. Accordingly, the development concept decided upon for the SH-AWD system was the realization of "neutral steering feel" turning characteristics that more accurately matched the intention of the driver.

2. Drive Force Control Theory

The maneuverability of a four-wheel drive vehicle is enhanced when a system that permits distribution of the drive

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force between the rear wheels and also distribution of the drive force between the front and rear wheels is used. This is because such a system enables the yaw moment to be controlled directly and can also maintain a uniform load on each of the four wheels. This theory is explained below.

2.1. Effectiveness of Difference in Lateral Drive Force

2.1.1. Yaw moment control

The basic control logic is assigned by Eqs. (1) and (2). The left and right drive forces applied to the rear wheels is controlled according to both the longitudinal acceleration and the lateral acceleration, enabling changes in the behavior of the vehicle (understeering and oversteering) to be reduced both during acceleration and deceleration⁽⁴⁾.

$$X_1 = \left(\frac{D_R}{2} + \frac{h}{tr} \cdot \frac{Y_G}{g} \right) \cdot \frac{W \cdot X_G}{g} \quad (1)$$

$$X_2 = \left(\frac{D_R}{2} - \frac{h}{tr} \cdot \frac{Y_G}{g} \right) \cdot \frac{W \cdot X_G}{g} \quad (2)$$

Where,

X_1 (X_2) : Drive force on the outside (inside) rear wheel

D_R : Rear wheel drive force distribution ratio

W : Weight of vehicle

Y_G : Lateral acceleration

X_G : Longitudinal acceleration

G : Acceleration of gravity

H : Height of center of gravity

Tr : Tread of rear tire

2.1.2. Reduction of the cornering force on the front wheels

While a vehicle is cornering, a yaw moment is applied to the vehicle, causing the cornering force on the front and rear wheels to change. Figure 1 shows a diagrammatic representation of this condition, and Eqs. (3) and (4) indicate the total cornering force on the front and rear wheels. The total cornering force on the front wheels is reduced in the amount M/l , and that on the rear wheels is increased in the amount M/l .

$$CF1 = \frac{b}{l} F - \frac{M}{l} \quad (3)$$

$$CF2 = \frac{a}{l} F + \frac{M}{l} \quad (4)$$

Where,

$CF1$ ($CF2$) : Front wheel (rear wheel) total cornering force

M : Yaw moment generated by the difference between the left and right drive forces

F : Centrifugal force

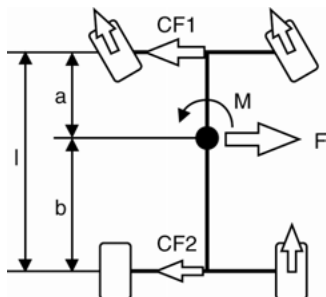


Fig. 1 Change of cornering force

2.1.3. Increase of cornering force

In a conventional drive system, the drive force on the left and right wheels is distributed evenly. As a result, tire friction is used as the main drive force, particularly on the inside wheel, hence only a small cornering force is generated.

By distributing a larger drive force to the outside wheel than the inside wheel when the vehicle is cornering, it is possible to generate a larger cornering force at the inside wheel as well.

The drive force during cornering and also the cornering force are indicated using a friction circle as below. Figure 2 (a) is applicable to a normal vehicle, and (b) to a vehicle that employs the SH-AWD system.

Figure 3 shows the cornering force versus torque distribution ratio on the inside and outside wheels. It can be seen that compared to an equal (50:50) distribution, the total cornering force on the left and right wheels increases as an increasing proportion of the drive force is applied to the outside wheel.

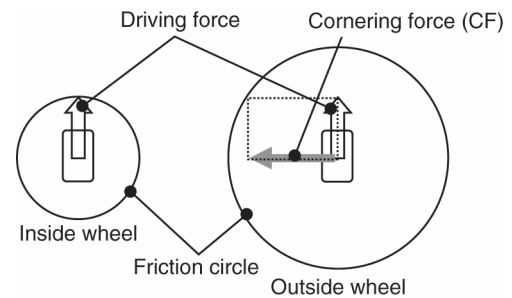


Fig. 2 (a) Tire force for conventional vehicle

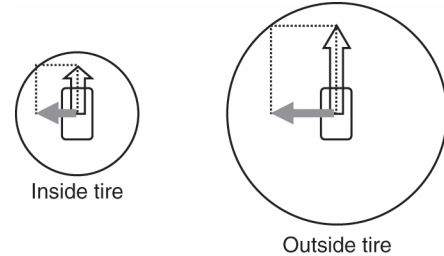


Fig. 2 (b) Tire force for SH-AWD

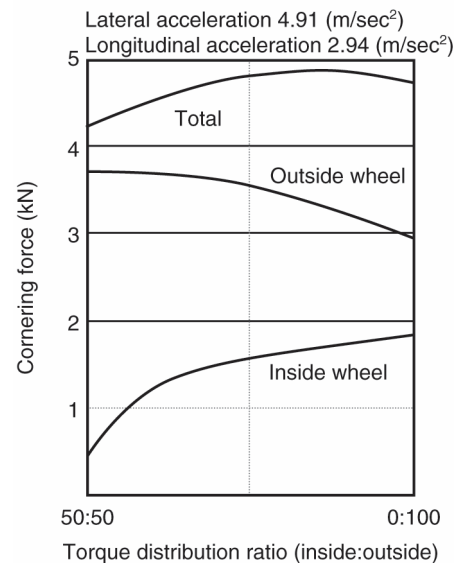


Fig. 3 Effect of torque distribution

2.2. Equalizing the Tire Load on the Four Wheels

The ground contact load and the force generated at the tires change according to the degree of acceleration and cornering. The tire load ratio is defined by Eq. (5) as the ratio of the generated force to the maximum force that can be generated.

$$\eta = \frac{\sqrt{F_x^2 + F_y^2}}{\mu \cdot W} \quad (5)$$

Where,

H : Tire load ratio

F_x : Tire drive force

F_y : Tire side force

M : Road surface coefficient of friction

W : Tire ground contact load

Figure 4 shows the change of the tire load ratio with respect to the lateral acceleration. By equalizing the load ratio at the four wheels, it is possible to increase the lateral acceleration that can be generated, to the maximum limit, and thus enhance the cornering performance.

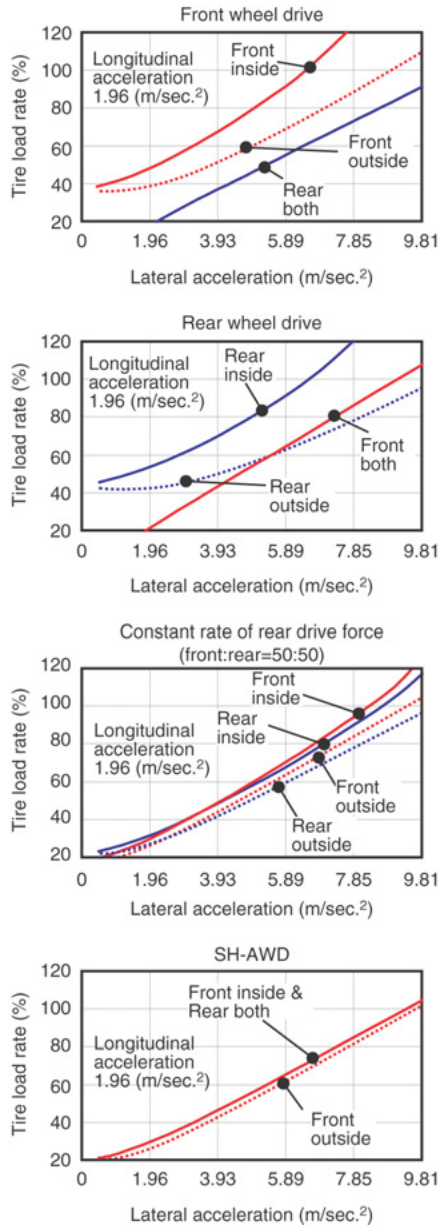


Fig. 4 Load rate of each wheel

3. SH-AWD System

The following describes the principle of this system and the control method used.

3.1. System Configuration

Figure 5 shows the configuration of the vehicle system. In this system, data from the various sensors is inputted to a dedicated ECU (SH-AWD ECU) from the other ECUs via CAN communication. When this dedicated ECU detects the intention of the driver and the driving situation, the rear drive unit distributes the drive force to the left and right, and increases the rotational speed to the rear wheels. The rear drive unit is located at the rear of the propeller shaft and is controlled by instructions from the dedicated ECU.

Figure 6 is a cross-sectional diagram of the rear drive unit.

This unit consists of a two-speed shift unit which increases the input speed from the propeller shaft when the vehicle is cornering, a hypoid gear which converts the input rotation from the two-speed shift unit into the rotational speed of the left and right wheels, and a pair of direct left and right electromagnetic clutches that accurately control and distribute the drive force.

By applying more drive torque to the outside rear wheel when the vehicle is accelerating during cornering, an inward yaw moment is generated, reducing understeering. In the rear drive unit, the outer clutch of the left and right clutches, mounted on the rear wheel axle, is pressed harder. This enables more drive force to be applied to the outside rear wheel. This is how the above mentioned condition is attained.

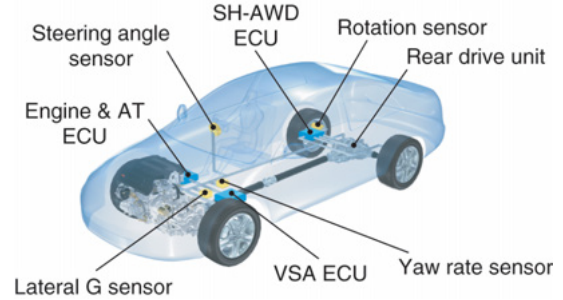


Fig. 5 System layout of SH-AWD system

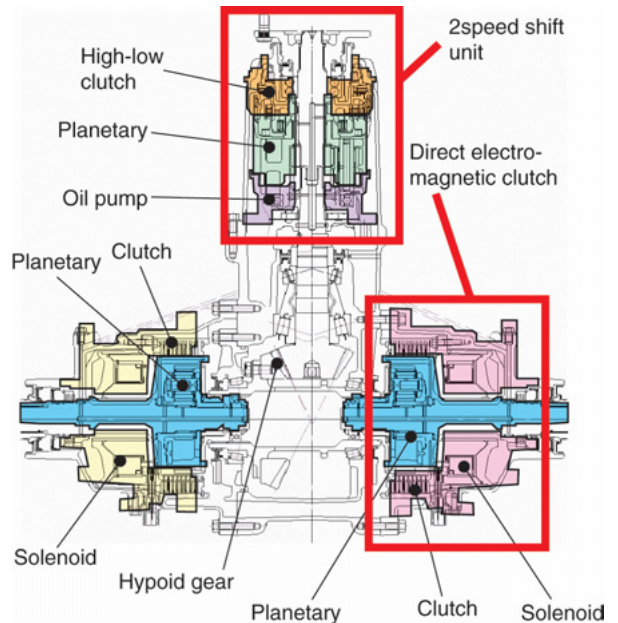


Fig. 6 Cross-section of rear drive unit

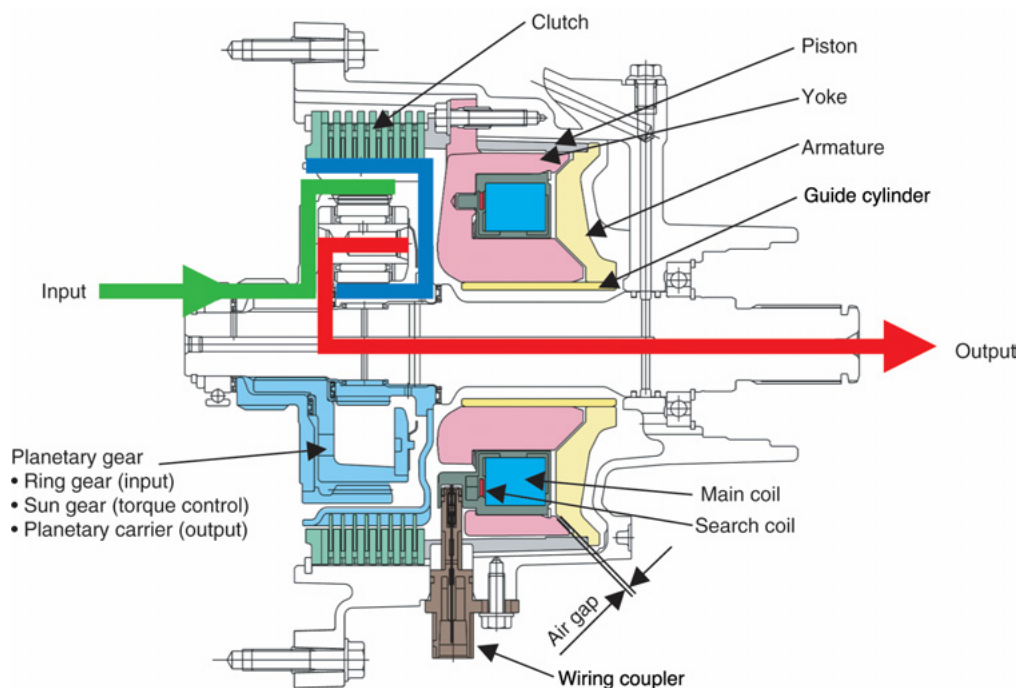


Fig. 7 Direct electromagnetic clutch section

3.2. Direct Electromagnetic Clutch

The electromagnetic clutch determines the drive force of the SH-AWD. It is required to have low hysteresis and linear torque characteristics. Therefore, the clutch is constructed in such a way that the transfer path of the attraction force is simplified. Also the attraction force generated by the electromagnetic solenoid acts directly on the clutch, thus minimizing elastic deformation.

3.2.1. Construction

Figure 7 shows the construction of the electromagnetic clutch. The magnetic circuit is formed by the armature and yoke. A low-hysteresis magnetic material was selected. The slider, which is press-fitted into the armature, centers the armature with respect to the yoke. It is made of non-magnetic material so that it does not form part of the magnetic circuit. A magnetic field is generated by energizing the electromagnetic coil fixed to the inside of the yoke. The yoke is subjected to a reactive force, created by the attraction force that acts across the air gap, because it is fixed to the side case. The attraction force generated at the armature acts directly on the clutch via the piston.

The torque from the propeller shaft is transmitted to the ring gear via the hypoid gear. The clutch is pressed by the armature via the piston, causing frictional force to be generated between the case and the sun gear. As a result, the torque input to the ring gear is boosted by the planetary gear set. The transmission torque of the clutch is multiplied by the planetary gear and outputted to the drive shaft via the planetary carrier. This torque amplifier enabled the electromagnetic clutch to be minimized in size.

The shape of the electromagnetic coil inside the search coil was selected so as to prevent ingress of lubricating oil. This was done by removing the fixing pin of the internal coil, during the resin molding process, in order to eliminate the resin boundary face. As a result, reliability was obtained, which ensures positive operation under the severe environment inside the rear drive unit.

3.2.2. Electromagnetic solenoid

The direct electromagnetic clutch was constructed so that the attraction force acted directly on the clutch. As a result, the air gap between the yoke and the armature changes due to the wear of the clutch, affecting the torque characteristics versus current. Figure 8 shows the empirical results of the torque characteristics versus the air gap for different magnetic circuit profiles (tapered and flat). By using a tapered magnetic circuit, stable torque characteristics with respect to changes in the air gap were obtained. It was also possible to obtain a higher attraction force over the range of the gap used.

Figure 9 shows the relationship between magnetic flux and torque. There is correlation between them, so it is possible to estimate the torque from the magnetic flux.

Here, in order to measure the magnetic flux, a method employing a search coil was developed. Concretely, this method detects the magnetic flux from the voltage generated in the search coil when the prescribed current is passed through the main coil. Figure 10 is a map that shows the relationship between the current, magnetic flux and torque.

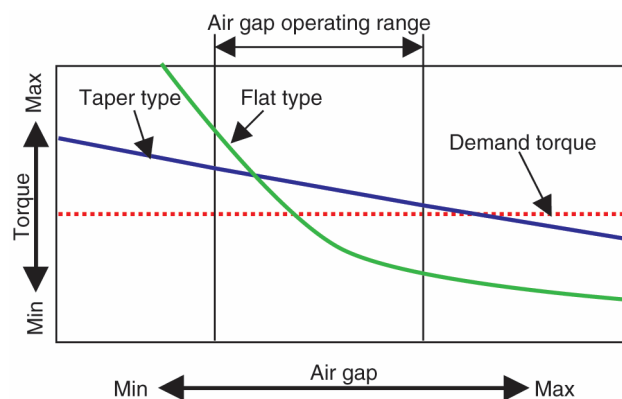


Fig. 8 Air gap-taper/flat torque characteristic

Based on the detected magnetic flux, the current that flows in response to the target torque is obtained from the above map. By correcting this current, it was possible to obtain correlation between the target torque and the actual torque for different air gaps. Figure 11 shows the test results when no correction was made, and Fig. 12 the results when correction was made.

3.2.3. Clutch

In order to fully control torque transmission, the clutch is continuously slip-controlled. The slip ratio is determined by the differential rotation of the front and rear wheels, so it is affected by the vehicle speed and the slip of the tires. If the friction characteristics are not stable, unpleasant vibration will occur.

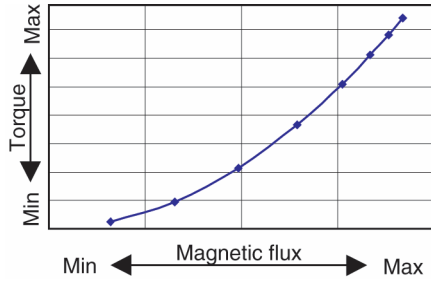


Fig. 9 Magnetic flux-torque characteristic

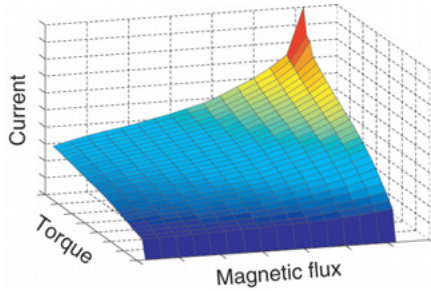


Fig. 10 Current-torque magnetic flux map

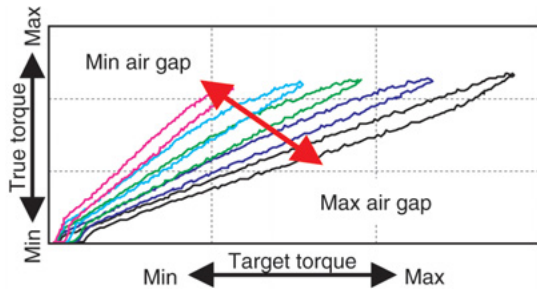


Fig. 11 Torque characteristic without magnetic flux correction

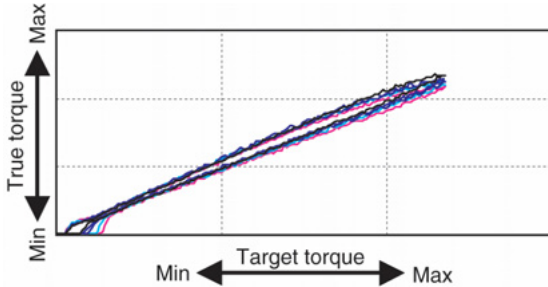


Fig. 12 Torque characteristic with magnetic flux correction

Also, as the clutch wears, the gap between the yoke and the armature will decrease until the yoke and armature strike each other, preventing an attraction force from being generated. If the air gap is made sufficiently large in order to prevent this, the torque capacity will fall, as can be seen from Fig. 8. Consequently, it is necessary that the clutch has stable friction characteristics and wear resistance.

The area where the surface pressure is low is advantageous for obtaining stable torque characteristics. For this reason, the previously mentioned torque amplifier was used to reduce the pressing load of the clutch, permitting the area where the surface pressure was lower than that of the AT and CVT to be used, as shown in Fig. 13.

Figure 14 shows the relationship between the absorbed energy and the clutch abrasion. The clutch abrasion is initially high, so an initial familiarity process was added to reduce initial abrasion.

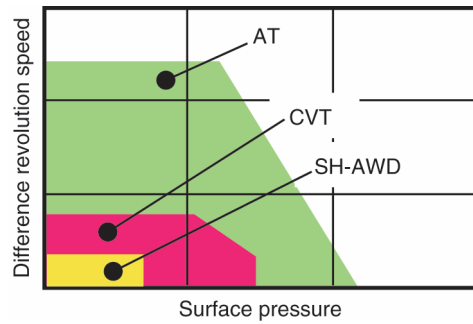


Fig. 13 Surface pressure image

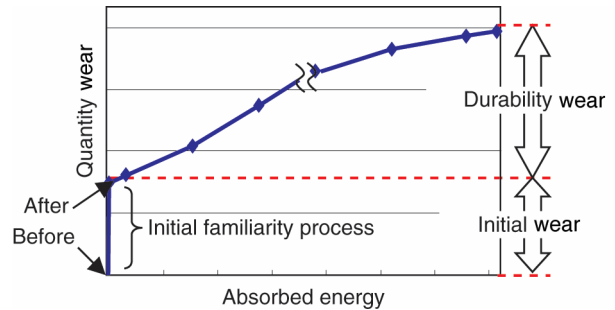


Fig. 14 Quantity of clutch wear

3.3. Principle of High Range

Figure 15 shows the trace line of the four wheels during cornering. The trace line of the outside rear wheel is outward of the average trace line of the front wheels. Figure 16 shows the ratio of the outside rear wheel velocity to the average velocity of the front wheels, versus the angle of front wheel. As soon as the vehicle corners, the outside rear wheel rotates faster than the average velocity of the front wheels. When the clutch is engaged in this condition, the outside rear wheel decelerates. In other words, resistance is generated with respect to the road. In order to avoid this, it is necessary to increase the speed of the propeller shaft and transmit this increase to the rear wheels. For this reason, it was decided to install a two-speed shift unit in all vehicles fitted with a SH-AWD system.

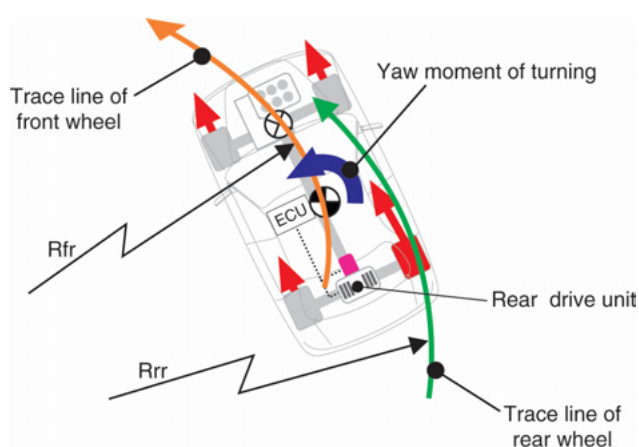


Fig. 15 Movement of vehicle in turning

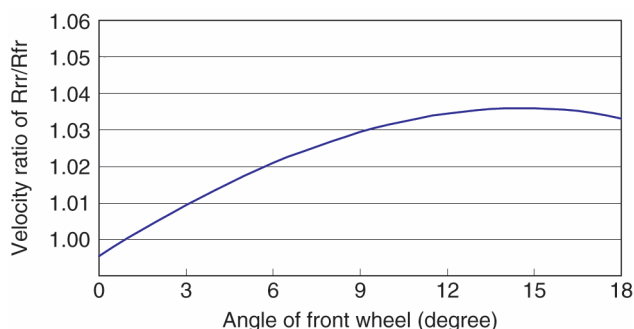


Fig. 16 Velocity ratio of rear to front wheel

3.4. Two-speed Shift Unit

It is necessary to reduce minimize the two speed shift unit size because it is installed under the bottom of the fuel tank and to ensure that there is adequate clearance above the ground. In order to realize this, the unit was designed so that the two clutches could be switched over with a single hydraulic actuator. A planetary gear, one-way clutch and a dedicated reversing clutch were also used.

3.4.1. Construction

Figure 17 is a cross-sectional diagram of the two-speed shift unit. The unit consists of a sun gear on the input shaft and a sun gear on the output shaft which have different numbers of teeth, a twin pinion consisting of a combination

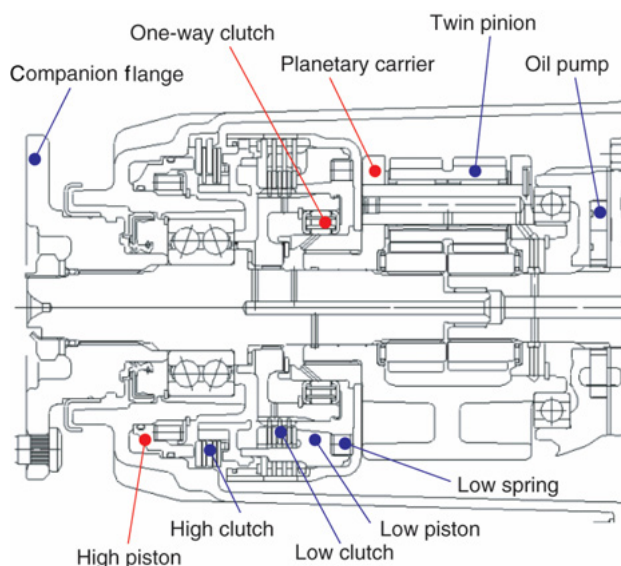


Fig. 17 Cross-section of 2speed shift unit

of two pinion gears which mesh with these sun gears, a planetary carrier which supports this twin pinion, a one-way clutch and low clutch which couple the planetary carrier to the input shaft, and a high clutch which couples the abovementioned carrier to the case.

When the vehicle is moving forward, the low clutch is pressed to the low spring via the low piston, causing it to engage. As a result, the planetary carrier and input shaft rotate as one body in a low range state. The pinion gear does not revolve about its own axis, but instead revolves together with the carrier.

When the vehicle is cornering, the high piston, built into the case, generates a load by hydraulic pressure. As a result, the high clutch is pressed, causing it to engage, and also the low spring is compressed via the low piston, causing the low clutch to disengage. When the high clutch engages, the planetary carrier is fixed to the case, causing the pinion gear to stop revolving. Along with this, the pinion gears mesh with the sun gears on the input and output shafts, and rotation begins. The difference in the gear ratio at these two points results in a high range condition.

The one-way clutch was assembled in a manner such that the planetary carrier does not overtake the rotation of the input shaft when the vehicle is advancing. As a result, the carrier and the input shaft rotate as one body when the vehicle is accelerating in the forward direction. For this reason, the unit was constructed in such a way that it had a low range function, and did not prevent the carrier from being fixed when the vehicle was accelerating. The low range function, used when the vehicle is accelerating in the forward direction, is performed by the one-way clutch, which enables the size of the dedicated engine brake clutch intended for reversing and decelerating to be minimized.

3.4.2. Hydraulic control system

Figure 18 shows the hydraulic circuit diagram.

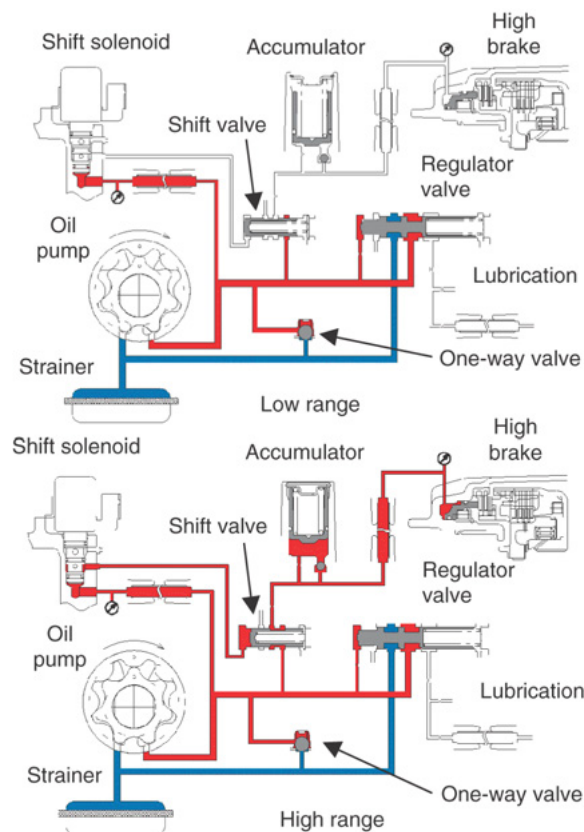


Fig. 18 Diagram of hydraulic circuit

This system consists of an oil pump that rotates together with the propeller shaft, a regulator valve that regulates the line pressure, a shift valve that switches between one clutch and the other, a solenoid that controls the shift valve, a hydraulic accumulator, and a one-way valve.

The oil that is discharged when the pressure is being regulated by the regulator valve was used as lubrication oil. Also, when the pressure of the lubrication oil reaches a certain level, the discharged oil is returned to the inlet port of the oil pump in order to protect the circuit, leveling the amount of lubrication oil and reducing the load on the oil pump.

The solenoid moves the shift valve based on instructions from the dedicated ECU, recirculating the line pressure to the clutch chamber, and controlling the discharge of residual oil in the clutch chamber.

The one-way valve recirculates the oil from the discharge port to the inlet port of the oil pump when the vehicle is reversing. This prevents a delay in response and also the occurrence of cavitation due to inclusion of air in the hydraulic circuit when the reverse-rotating oil pump is switched over to forward rotation. It also prevents the outflow of contaminants from the strainer due to reverse flow.

4. Vehicle Control System

4.1. Control Logic

Figure 19 shows the control flow chart for the SH-AWD. Emphasis was placed on the response of the system, and mainly feed-forward control was used. In feed-forward control, the control quantity is determined based on predetermined vehicle characteristics, which results in the possibility of the control accuracy being reduced by changes in the vehicle characteristics or changes in the environment, such as the road surface. For this reason, logic correction by feedback control was used.

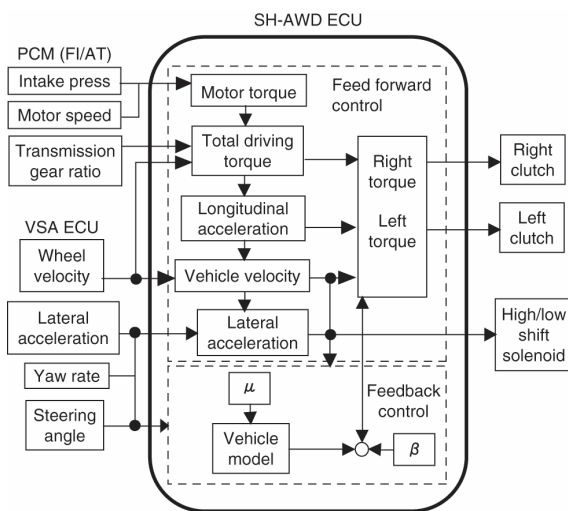


Fig. 19 Chart of control flow for SH-AWD system

4.2. Feed-forward Control

The control flow of feed-forward control is described below.

- The torque generated by the engine is estimated from the engine speed, manifold vacuum, and so on, referring to a preset torque map.
- The total drive torque on the axle is converted from the transmission gear ratio, the torque ratio of the torque converter, and so on.
- The front to rear wheel torque distribution ratio is set

according to the driving situations such as running speed, transmission gear ratio, and throttle opening.

- The rear wheel torque is calculated from the total drive torque and front-rear wheel torque distribution ratio.
- The extent of cornering is calculated from the estimated lateral acceleration based on the average velocity of the rear wheels, steering angle, lateral acceleration sensor, and the yaw rate sensor.
- Each of the left and right rear wheel drive torques is calculated based on the extent of cornering.
- Each of the left and right rear wheel drive torques is output to the electromagnetic clutch as a current setting.

4.3. Feedback Control

The control flow of feedback control is described below.

- The vehicle body slip angle at the center of gravity is estimated based on a vehicle model.
- An estimated slip angle is compared to the slip angle threshold that corresponds to the extent of cornering. When the slip angle is judged to be large, output is corrected to reduce the difference between the left and right rear wheel torque values obtained by the feed-forward control.
- In addition, if no tendency for decreased slip angle is observed, a corrected output reduces the ratio of distribution torque on the rear wheels.

4.4. Two-speed Shift Unit Control

High range control is performed only when cornering. In order to judge cornering, the absolute value of the lateral acceleration estimated by feed-forward control is used. The method whereby the estimated lateral acceleration is used enables the cornering motion to be predicted from the driver's input. In this respect, it produces a better response compared to the case where the output from the lateral acceleration sensor is used.

Figure 20 shows the driving situation under which the front wheel average velocity and rear outside wheel velocity are equal when this system is in a low range condition, in terms of the relation between the vehicle velocity and the lateral acceleration. From Fig. 20, it can be seen that the value of the lateral acceleration requiring high range increases in proportion to the vehicle velocity. Consequently, a high range instruction is set to be output at the higher lateral acceleration value in the high velocity range.

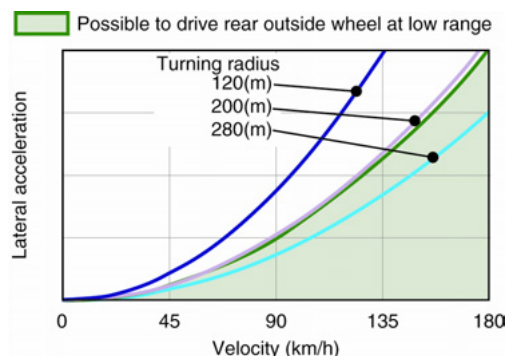


Fig. 20 Wheel speed relation at low range

5. Actual Vehicle Performance

The results of a running test carried out on a vehicle fitted with the SH-AWD are set out below. The vehicle was cornered and slalomed while accelerating. These examples illustrate the effectiveness of this system particularly well.

5.1. Acceleration Cornering Characteristics

A mechanical permanent four-wheel drive vehicle with a center differential that distributed the drive force evenly between the front and rear wheels was used as the comparison vehicle. Figure 21 shows the turning characteristics of the vehicle during acceleration. The vehicle was fully accelerated from a base circle cornering condition (steady state) in which the vehicle was moving at a very low fixed speed and a fixed steering angle, and the spread of the turning radius was evaluated in terms of the rate of change with respect to the base circle radius. It was found that a vehicle fitted with the SH-AWD produced a lower increase in turning radius and significantly less understeer compared to the comparison vehicle. In addition, the limit lateral acceleration at which cornering was possible increased significantly.

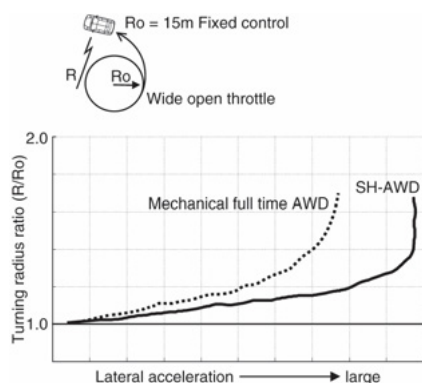


Fig. 21 Turning radius ratio against lateral acceleration

5.2. Slalom during Acceleration

The yaw rate response with respect to the steering angle when the vehicle was slalomed while abruptly accelerating was evaluated. Figure 22 shows the results for a front wheel drive vehicle, and Fig. 23 shows the results for a vehicle fitted with the SH-AWD. In the case of a front wheel drive vehicle, it was found that the yaw rate response worsened by continuous steering, and also the gain fell. In contrast, the vehicle fitted with the SH-AWD had better response, and also the divergence of the yaw rate was minimized due to the use of high gain. Thus both enhanced response and stability were achieved. (Shaded area of the figure)

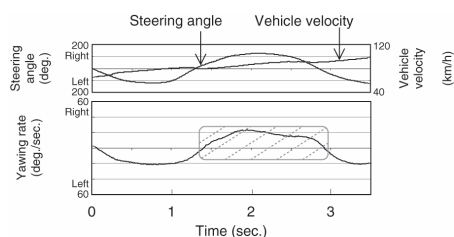


Fig. 22 Result of front wheel drive vehicle

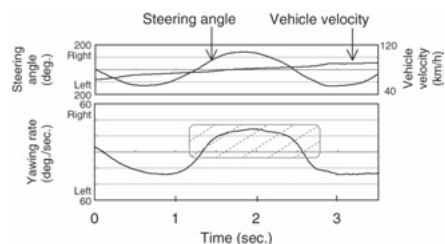


Fig. 23 Result of SH-AWD vehicle

6. Conclusion

By fully controlling the distribution of drive force

between the front and rear wheels, and also the drive force of the left and right rear wheels, it was possible to achieve cornering performance that more accurately reproduced the steering operation, and also a high yaw rate response to the steering angle. As a result, a "neutral steering feel" was achieved in which the turning characteristics were a more accurate reproduction of the driver's intent.

Also, as a result of devising current correction control utilizing a direct electromagnetic clutch and search coil, it was found possible to control the drive force with higher accuracy. In addition, the use of a miniaturized two-speed shift unit enabled the unit to be readily installed under the vehicle, thus widening the range of cornering control.

In this SH-AWD development, many new developments were performed concerning each technological element individually. In this paper, an overall description of the system was given. In the future, the authors would like to obtain an opportunity to introduce each technological element independently.

Finally, the authors would like to express their heartfelt appreciation to the people who provided valuable assistance in the development of this system.

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