

Development of a Compact CVT for a Hybrid Car – Insight

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ABSTRACT

The continuously variable transmission (CVT) used in the Insight, a hybrid car, was developed using the basic construction of Honda's conventional CVT but with the aim of lighter weight, smaller size, and greater efficiency. This CVT optimizes line hydraulic pressure by utilizing a direct control system for pulley hydraulic pressures and differentiated drive-driven pulley pistons. The mechanism also uses such means as lubricant pressure control to reduce friction in each part, expand the ratio range, and improve the efficiency of engine-motor cooperative control. Further, the utilization of such devices as a forward-reverse select mechanism that operates with a single-pinion planetary gear served to reduce the number of parts.

1. Introduction

The continuously variable transmission (CVT) used in the 1996 model Civic (hereafter the “conventional CVT”) is an automatic transmission which simultaneously achieves both drivability and fuel economy with an original construction which locates the start clutch on the driven pulley axle and by electronically controlling the three factors of starting, shifting and the belt side pressure.⁽¹⁾ (Side pressure is the pressure applied to the V belt in the lateral direction.) The 1999 model further enhanced product appeal by adopting PROSMATEC (Progressive Shift Schedule Management Technology) which performs control to select the optimum gear ratio even on roads with numerous hill climbs and descents, and 4WD was also added as a variation.

The conventional CVT has high fuel economy performance, but research has continued since the Civic's release to further reduce friction, improve efficiency and reduce costs.

When developing the new CVT used in the Insight, the new technologies obtained through this research were combined with the Integrated Motor Assist (IMA) system, and an aerodynamic and lightweight aluminum body to achieve the ultra-low fuel consumption of 32 km/l.⁽²⁾ This CVT has been introduced a number of times thus far^{(3)~(5)}, and thus this paper mainly describes the changes from the conventional CVT.

2. Development Aims

When developing this CVT for use in the Insight together with the IMA system, the aim was to improve fuel economy. Reducing friction and expanding the ratio range are effective means of improving fuel economy.⁽⁶⁾ This CVT reduced the belt friction and the oil pump load, etc., to improve friction and expand the ratio range in order to improve fuel economy, and the weight and size were also optimized for the Insight. An additional aim was to improve product appeal by reducing the number of parts.

3. Basic Specifications and Construction

The basic specifications for this CVT are shown in Table 1. The total length is 23 mm shorter and the weight 7% lighter than the conventional CVT. In addition, the ratio range has

Table 1 CVT specifications

		Insight	Current CIVIC
Transmission ratio	Forward	2.441~0.407	2.466~0.449
	Reverse	4.401~2.441	2.466
	Final	5.688	5.809
Belt axis length (mm)		143	155
Transmission length (mm)		351	374
Transmission weight [wet] (kg)		72.3	79.5

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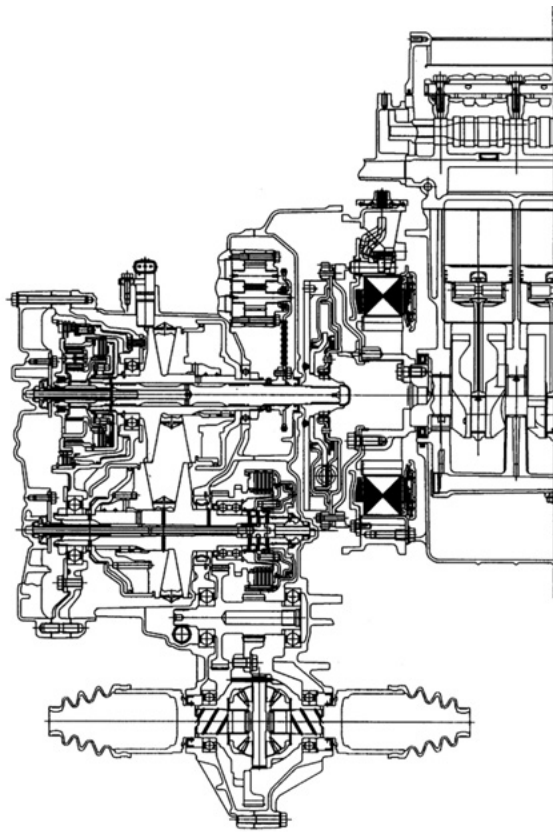


Fig.1 Insight CVT Main section drawing

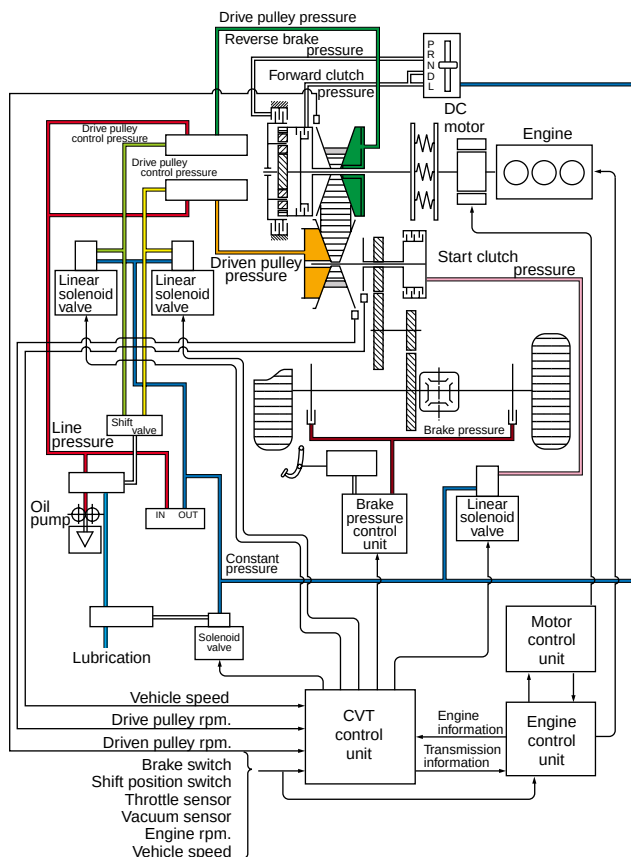


Fig.2 Insight CVT System drawing

been expanded from 5.5 to 6.0.

Fig. 1 shows the main section of this CVT, and Fig. 2 shows the control system.

First, the features of the construction are described below based on Fig. 1.

3.1. Input Block

The engine and motor drive torque are input by a drive plate coupled to the rotor, the torque fluctuation is attenuated by a dual mass flywheel, and the torque is transmitted to the input shaft. A sensor plate for sensing the motor phase is coupled to the drive plate. The input shaft drives the oil pump by a chain like the conventional CVT. In addition, the pitot's flange that was conventionally coupled to the input shaft for start clutch control back-up in the event of electrical system failure has been replaced with a back-up system inside the hydraulic circuit described hereafter.

3.2. Forward-Reverse Select Mechanism

The input shaft is coupled to the forward-reverse select mechanism, and neutral, forward and reverse are selected by the intermittent application of hydraulic pressure to the forward clutch and reverse brake. The forward-reverse select mechanism has been changed from the conventional double-pinion planetary gear to a single-pinion planetary gear. This resulted in the number of gear mesh points being reduced two-third compared to previous, and the working frequency has been halved to reduce high frequency noise and gear noise during reverse, thus improving product appeal. In addition, the single-pinion planetary gear makes the reduction ratio 1.8 times compared to the previous ratio, but the load on the metal belt was reduced and drivability during reverse was improved by the cooperative control with the engine described hereafter and quick shifting. Fig. 3 shows a comparison with the conventional CVT.

3.3. Transmission

After passing through the forward-reverse select mechanism, the drive torque is shifted and transferred from the drive pulley to the driven pulley by a metal belt. The basic CVT specification of the pulley axle center distance was set at 143 mm which is the optimum value in terms of the IMA output characteristics compared to 155 mm for the conventional Civic. This made it possible to reduce the housing and pulley circumference size and the weight.

The metal belt was made by Van Doornes Transmission, and had a new element shape with the ring composition changed from two rows of 12 rings to two rows of 9 rings to reduce friction. The drive and driven piston shapes used different outer diameters to obtain the greatest effect from the direct control system for pulley side pressures, and the oil pump load when cruising was reduced by setting the area of the drive side piston which normally has greater thrust force to 1.3 times that of the driven side piston. (See Fig. 4.)

3.4. Start Clutch

The basic construction is the same as the conventional CVT. However, when restarting from idle stop, the hydraulic pressure must be raised quickly from the condition where hydraulic pressure is not produced to allow starting.

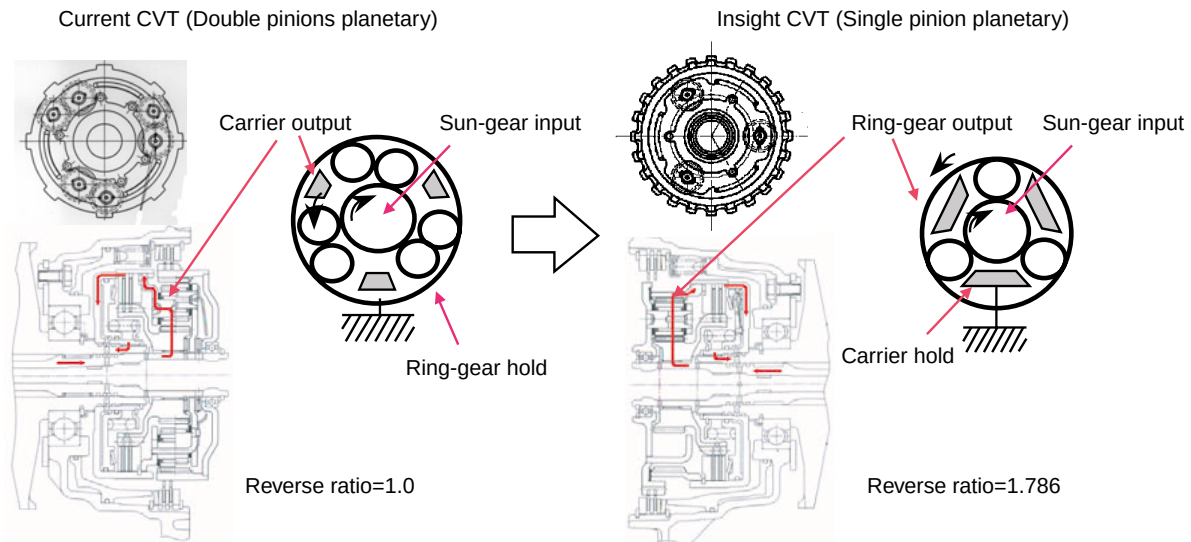


Fig.3 Reverse system comparison

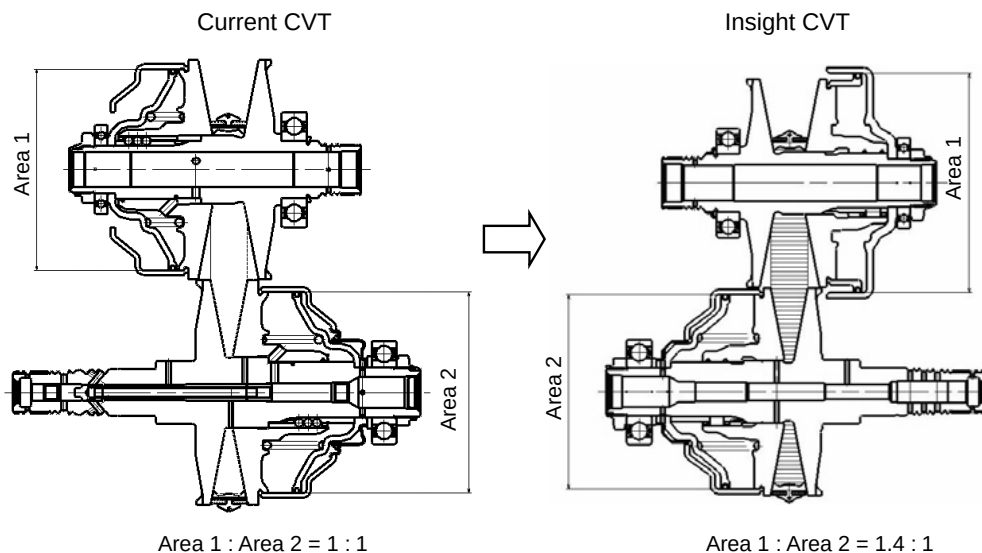


Fig.4 Pulley system comparison

Therefore, the sealing properties of the valve body were improved, dead volume was reduced by shortening the hydraulic circuit, and the control accuracy was improved to allow quick and smooth starting.

3.5. Final Reduction

Changes in gear noise caused by torque fluctuation when decelerating were reduced by setting the twisting direction of the secondary gear with respect to the rotating direction opposite that of the conventional CVT and by decreasing the relative displacement of lead slant when decelerating. The differential gear size was reduced and weight reduction for the differential case was exhaustively pursued by FEM analysis resulting in a weight reduction of approximately 5% compared to other differentials in the same class.

3.6. Hydraulic Pressure Control System

Next, the control system is described. Fig. 5 shows the hydraulic circuit diagram. The conventional CVT is

comprised of a side pressure control system which controls the pulley side pressure and a shift control system which controls the thrust force of the drive and driven pulleys. However, in the new CVT this has been changed to a direct control system for pulley side pressure which controls the drive and driven pulley side pressures independently. This makes it possible to optimize the drive and driven pulley hydraulic pressures in any operating condition, thus greatly reducing the oil pump load. Fig. 6 shows a comparison with the conventional system.

The hydraulic pressure control system has the configuration shown below.

3.6.1. Pulley Side Pressure Control System

The conventional CVT control system used a four-way valve to distribute the control hydraulic pressures of the two high pressure and low pressure systems to the drive and driven pulleys according to the input torque and gear ratio. The newly adopted direct control system for pulley side pressures adjusts the line pressure according to the signal

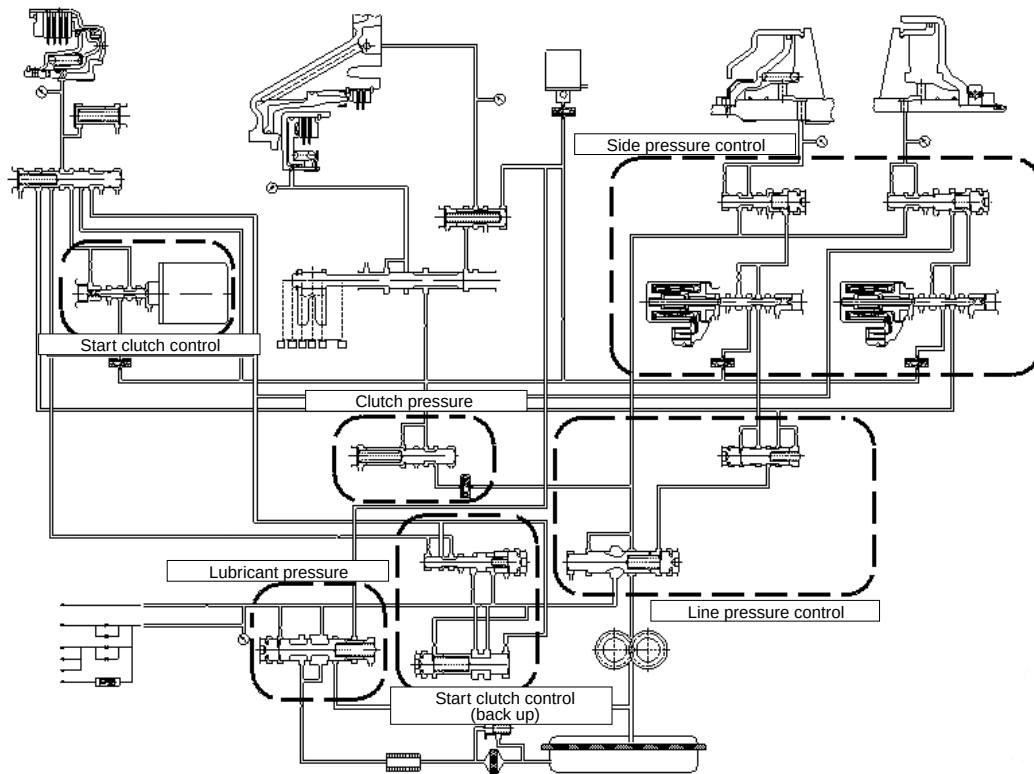


Fig.5 Hydraulic circuit

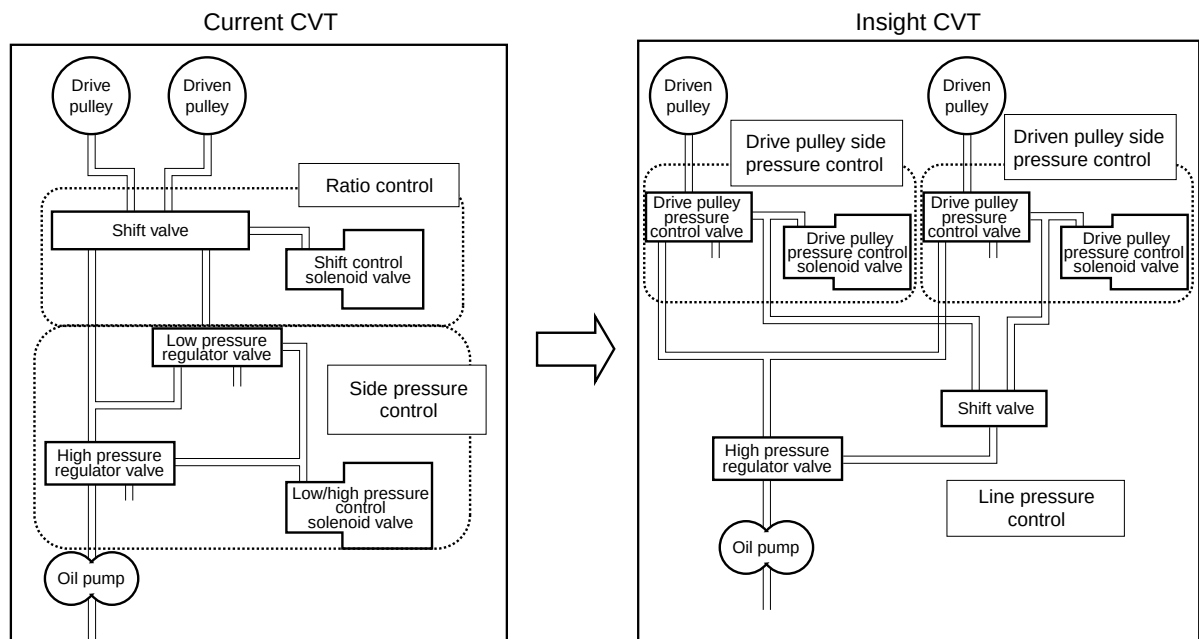


Fig.6 Pressure control system

pressures of independent linear solenoid valves and supplies the drive and driven pulley side pressures to the respective pistons.

3.6.2. Line Pressure Control System

The conventional system has a construction which controls the low pressure, which is the side pressure needed for the pulleys to transmit torque, and the high pressure, which adds to this the hydraulic pressure difference needed

for shifting according to the signal pressure of the linear solenoid valves. This hydraulic pressure difference is the pressure difference needed for quick shifting, and becomes excess hydraulic pressure during normal cruising. In the new CVT, the hydraulic pressure from the oil pump is adjusted using regulator valves and supplied to the drive pulley control valve and driven control valve. The regulator valves select the higher of the linear solenoid valve signal pressures that

control the drive and driven pulley hydraulic pressures with a shift valve, and control the line pressure as the control signal pressure. This means that the line pressure has the minimum margin pressure added to the necessary pulley pressure, thus reducing excess hydraulic pressure. (See Fig. 7.)

3.6.3. Clutch Pressure Control System

The clutch pressure is supplied as hydraulic pressure which has been attenuated by a modulator valve with the line pressure as the hydraulic pressure source. This hydraulic pressure is used as the hydraulic pressure source for the linear solenoid valves which control the forward clutch, reverse brake and start clutch.

3.6.4. Start Clutch Control System

The start clutch is controlled by adjusting the hydraulic pressure with a linear solenoid valve in the same manner as the conventional CVT.

3.6.5. Lubricant Pressure Switching Control

Lubricant pressure switching control was adopted to reduce the oil stirring friction. Lowering the oil surface height inside the transmission as much as possible is an effective means of reducing the stirring friction. The oil surface height is determined so that aeration does not occur at low temperatures, but the oil surface rises causing the stirring

friction to increase at high temperatures. Therefore, the stirring friction was reduced by controlling the lubricant pressure and lubricant flow rate to thereby optimize the oil surface height. The lubricant pressure is set by controlling the solenoid valve according to the oil temperature and vehicle speed conditions and switching the signal pressure to the lubricant pressure control valve. This control is realized without adding devices by the combination of the conventional reverse inhibitor solenoid valve control logic.

3.6.6. Start Clutch Back-up

This control block comprises a system for switching from electronic control to hydraulic pressure control to assure operating performance as a back-up function for the electronic control system. The back-up system for the conventional CVT controlled the start clutch with a governor circuit which used the total pressure corresponding to the engine speed produced by the pitot's flange provided on the input shaft. The pitot's flange constantly rotates and thus it is a source of friction. In this CVT, a system having the same functions as the pitot system was provided inside the control body. Focusing on the fact that the lubricant flow rate changes according to the engine speed, the start clutch pressure is controlled according to the engine speed by applying the difference in hydraulic pressure produced by the lubricant passing through an orifice to both ends of the back-up clutch pressure control valve as shown in Fig. 8. This eliminated the need for a pitot's flange, thus reducing friction and also the number of parts.

3.7. Electronic Control System

The CVT control unit processes a variety of input signals from various sensors and the engine control unit, and then drives the three linear solenoids and one ON/OFF solenoid that control the CVT, and the two ON/OFF solenoids for the auxiliary brake system for starting on hills. In addition, the CVT control unit communicates with the engine control unit to perform cooperative control related to idle stop. The CVT control unit functions are described below.

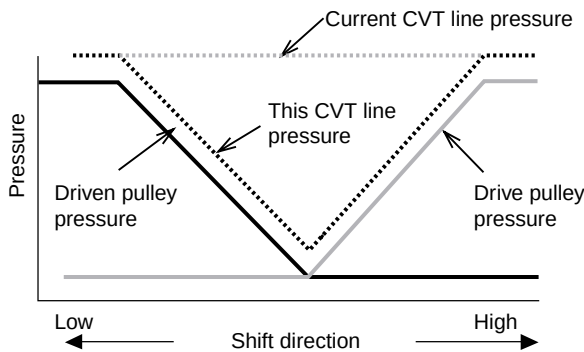


Fig.7 Pulley and line pressure

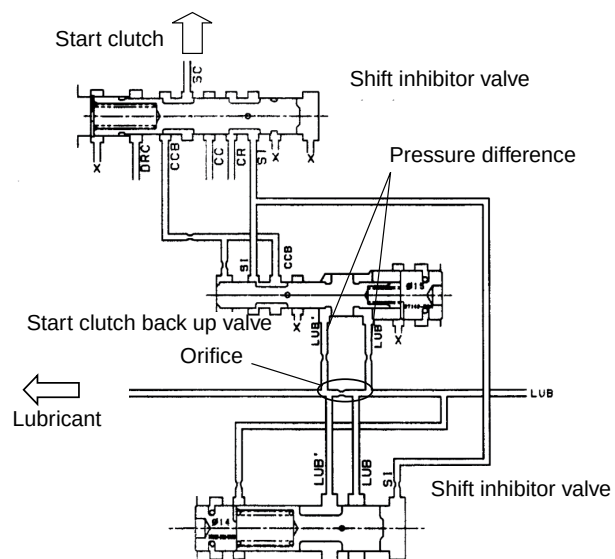
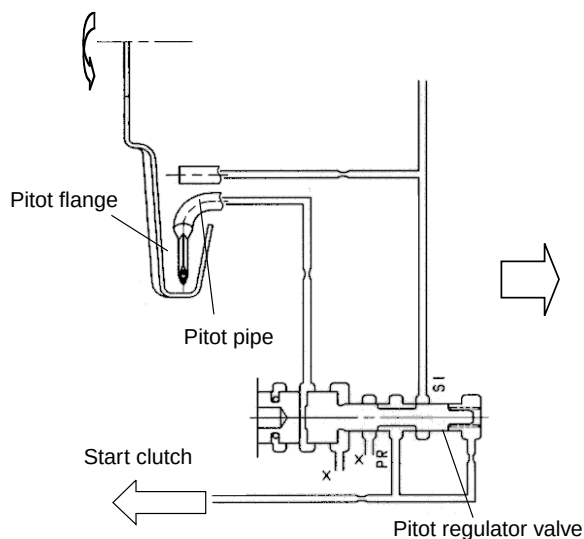


Fig.8 Starting clutch back up system

3.7.1. Input Sensors

A drive pulley rotation sensor, driven pulley rotation sensor, vehicle speed sensor and speedometer sensor (back-up) are used as the rotation sensors for each part. In addition, an engine rotation signal is obtained from the engine. The transmission rotation sensor was changed to a semiconductor type to improve rotation detection accuracy and allow detection at extremely low vehicle speeds.

The operation system sensors detect the shift position signal, mode switch signal, throttle opening angle signal and brake signal. The brake sensor determines whether the brake pedal is depressed, and is used for the auto idle stop judgment described hereafter and the engine restart signal. In addition, the engine intake pipe negative pressure is detected to estimate the engine output torque.

3.7.2. Output Devices

Three linear solenoids for controlling the drive pulley pressure, driven pulley pressure and start clutch pressure, and one ON/OFF solenoid used for both reverse inhibitor control and lubricant pressure switching are provided inside the CVT as output devices. In addition to these devices, the brake hydraulic pressure is maintained and released by two ON/OFF solenoids which control the auxiliary brake system for starting on hills. Creep torque is not produced during auto idle stop which automatically stops the engine while idling, so this system maintains the brake pressure for a certain time to ensure the same operability as the conventional system even when starting on hills from the idle stop condition.

3.7.3. Communication System

The CVT control unit performs cooperative control by exchanging various information with the engine control unit. The exchanged information includes the intake pipe negative pressure, motor torque and other information from the engine control unit, the shift position signal and retard request during

reverse from the CVT control unit, and the idle stop signal from both units.

3.7.4. Pulley Side Pressure Control

Conventional control consisted of side pressure control which calculated the target pressure with the input torque and ratio as parameters and controlled the control valves, and shift control which controlled a four-way valve to achieve the target engine speed. However, the side pressure control system in this CVT uses direct control of the pulley side pressures and has the control configuration shown in Fig. 9 to independently control the drive and driven pulley pressures.

The necessary thrust force is calculated from the pulley ratio and input torque (total of the engine torque and motor torque). The shift schedule is determined by the target engine speed according to the vehicle speed and throttle opening angle, and the thrust force ratio required for this control is set according to a thrust ratio map. The thrust for shifting is fed back to correct the error with the target engine speed. In this manner the target drive and driven pulley thrusts are obtained, the respective control solenoid drive currents are determined and the pulley side pressures are controlled.

3.8. CVT Control during Auto Idle Stop

During auto idle stop, the CVT control unit sends the auto idle stop signal and the regeneration for engine stop signal for stopping the engine smoothly to the engine control unit. When restarting, the clutch engagement pressure corresponding to the start clutch residual pressure is controlled to obtain a smooth starting feeling.

3.9. Oil Filter

Improving durability with respect to contamination of the hydraulic pressure control system is an important issue for transmissions which perform high accuracy, electronic

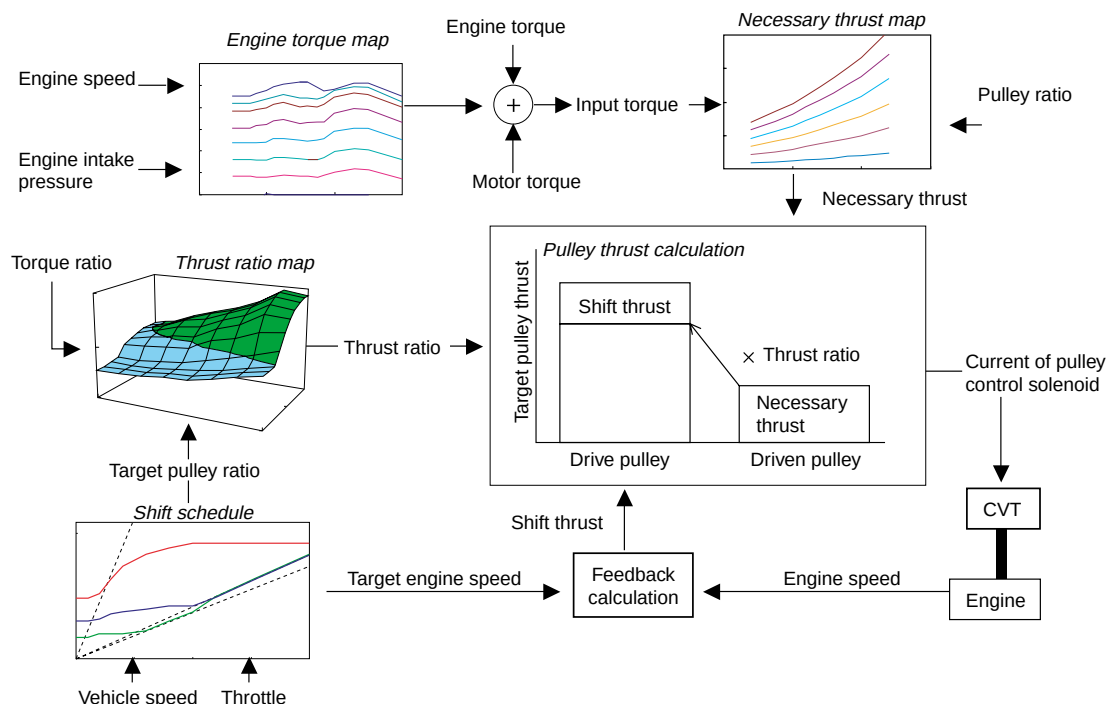


Fig.9 Pulley control block diagram

control using actuators. This CVT modified a non-woven fiber to improve the filtration performance of the oil filter. Increasing the filter material density and other methods of improving the normal filtration performance create such issues as increased pressure loss and shorter life due to early clogging. Therefore, the filtration performance was improved by increasing the types of fiber in the dual-layer non-woven fiber from the conventional one type per layer to multiple types per layer to reduce the gap between fibers, and the housing rib shape was optimized to prevent the non-woven fiber from sticking. These improvements increased the filtration efficiency from 1.5 to 2 times that of the conventional oil filter without increasing pressure loss or shortening the life. Fig. 10 shows a comparison of filter efficiency with the conventional oil filter. In addition, the housing was changed from pressed steel plate to plastic, thus reducing the weight by 50% compared to the conventional oil filter housing.

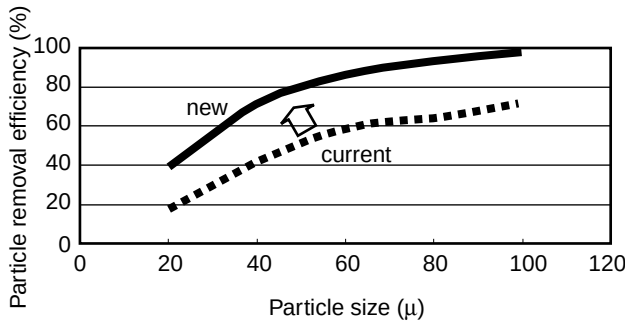


Fig.10 Oil filter efficiency

4. Adopted Technologies

Next, the three technologies adopted in this CVT are described.

4.1. Broad Gear Ratio

Setting a higher ratio allows the engine speed to be reduced when cruising and also during decelerating regeneration for hybrid vehicles, which is extremely advantageous for improving fuel economy. The low ratio is determined according to hill climbing capability which is obtained by the vehicle weight, tire diameter and engine output, and product appeal in terms of starting performance. However, a high top ratio is demanded to improve fuel economy. Therefore, the ratio range must be widened to simultaneously achieve both types of performance.

Expanding the ratio range of standard transmissions causes the step ratio to increase, so this is generally done by increasing the number of steps. However, this increases the number of parts which makes the transmission bigger and heavier. Metal belt CVTs can change the ratio range without increasing the number of parts by reducing the belt winding radius, but they are also limited by the following factors:

- Belt durability
- Shaft strength due to a narrower shaft diameter
- Increased length in the transmission axle direction

The ratio ranges of Honda and other automobile CVTs

sold prior to the Insight were approximately 5.0 to 5.5.

Therefore, the above factors were resolved as follows.

The issue of belt durability was solved by changing the over drive ratio according to the load. A ratio of up to 0.450 was used at high loads, and a high ratio of up to 0.407 was used at low loads, while cruising or during decelerating regeneration. Fig. 11 shows the shift map.

The issue of shaft strength was solved by performing FEM analysis to reduce the shaft diameter. In addition, the slide spline ball was replaced with a roller to shorten the dimension in the transmission axle direction while still ensuring sufficient power transmitting capacity. Furthermore, this greatly improved the power transmitting capacity, so the number of spline grooves was reduced from the conventional three grooves to a single groove.

These measures expanded the ratio range from the 5.5 of the conventional CVT to 6.0, and helped to improve fuel economy while cruising.

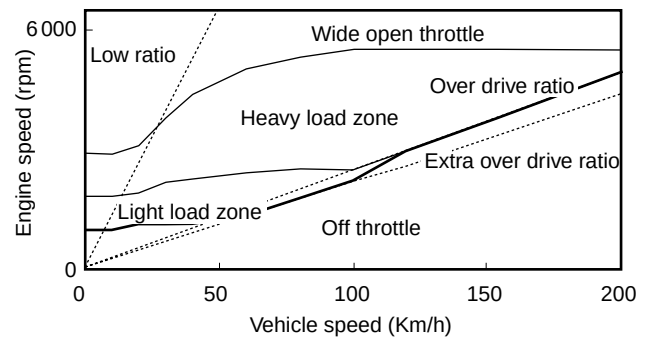


Fig.11 Shift limit lines

4.2. Direct Control for Pulley Side Pressures

The following issues were solved by adopting differentiated pulley pistons and a direct control system for pulley side pressures.

4.2.1. Reducing Hysteresis between Current and Hydraulic Pressure Characteristics

Reducing the pulley side pressure variance relative to the command current value reduces the specified side pressure margin with respect to the actual required side pressure, that is to say the excess hydraulic pressure. This also reduces the belt rotation friction, and is advantageous for improving belt durability. The magnetic materials of the linear solenoids used in this CVT were changed to materials with low hysteresis characteristics, which reduced the pulley pressure variance relative to the command current value by approximately 30% compared to the conventional CVT.

4.2.2. Reducing Hydraulic Pulsation

Low frequency hydraulic pulsation produced by the delay in the pilot pressure response relative to the pulley pressure fluctuation was formerly an issue. This low frequency hydraulic pulsation directly influences the pulley thrust force fluctuation, so the solenoid valve response was improved.

The improvement method consisted of investigating the shape of the pressure adjusting end in terms of the balance between improving the solenoid valve flow rate characteristics and reducing the self-excited vibration of the

valve, and optimizing the spring constants.

4.2.3. Reducing Line Pressure Surge

The direct control system for pulley side pressures has a configuration which controls three hydraulic pressures with two solenoids, and the higher pulley pressure control solenoid also simultaneously controls the line pressure. Therefore, continuous surge tended to occur at low oil temperatures due to the delay in response relative to the high pressure side line pressure fluctuation. To resolve this issue, the damping characteristics of the line pressure control valve were optimized.

As a fail-safe measure, this system uses a reverse theory system which produces the maximum pressure in the condition where the control power supply has been cut off. Therefore, surge produced by the valve operation delay when starting the engine was also an issue. This surge was reduced by optimizing the command hydraulic pressure.

Resolving the above issues made it possible to use direct control and to reduce the excess hydraulic pressure. In addition, the above-mentioned lubricant pressure switching control, elimination of the pitot's flange and other measures greatly reduced friction and improved transfer efficiency. Fig. 12 shows a comparison of friction when cruising.

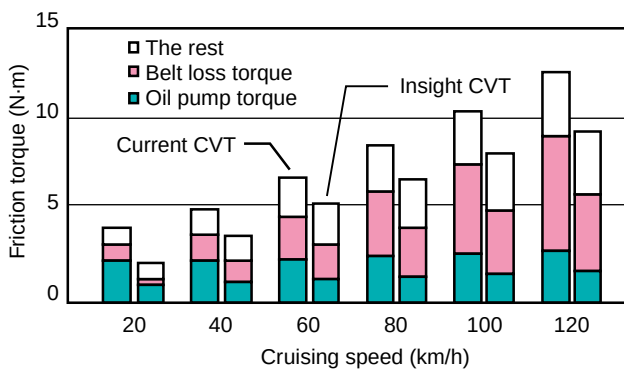


Fig.12 Transmission friction

4.3. Control of the Forward-Reverse Select Mechanism Using a Single-Pinion Planetary Gear

The forward-reverse select mechanism uses a planetary gear in consideration of easy operation and smooth switching. The conventional CVT used a double-pinion planetary gear which allowed the same gear reduction ratio to be set for both the forward and reverse steps to facilitate side pressure control. However, the large number of parts created the issues of increased cost and weight. This CVT focused on reducing weight, and was able to use a single-pinion planetary gear by performing cooperative control between the engine and CVT. The issues involved in using a single-pinion planetary and methods for solving these issues are described below.

The single-pinion planetary gear of this CVT uses a sun-gear input/ring-gear output to form the reverse gear shape. In this case, the reverse gear ratio is 1.786 times the forward gear, and the torque during reverse is amplified, resulting in insufficient side pressure.

The belt ratio is low in the in-gear condition during reverse. When the accelerator pedal is depressed the necessary side pressure is reduced, so the belt is shifted to the target ratio. In this case some time is required to shift the belt from the low ratio to the target ratio, so insufficient side pressure may occur during the shift. In addition, excess drive power may be output with respect to forward, thus worsening drivability. This CVT locates the start clutch on the driven pulley side, so the power transmitting capacity is controlled to the same degree as during forward to ensure sufficient side pressure. In addition, cooperative control is performed to control the engine speed so that there is no feeling of an abnormal rise in rpm and to prevent an unnatural feeling in terms of drivability when starting.

Fig. 13 shows the control logic for engine/CVT cooperative control during reverse starting. When the accelerator pedal is depressed from the reverse gear in-gear

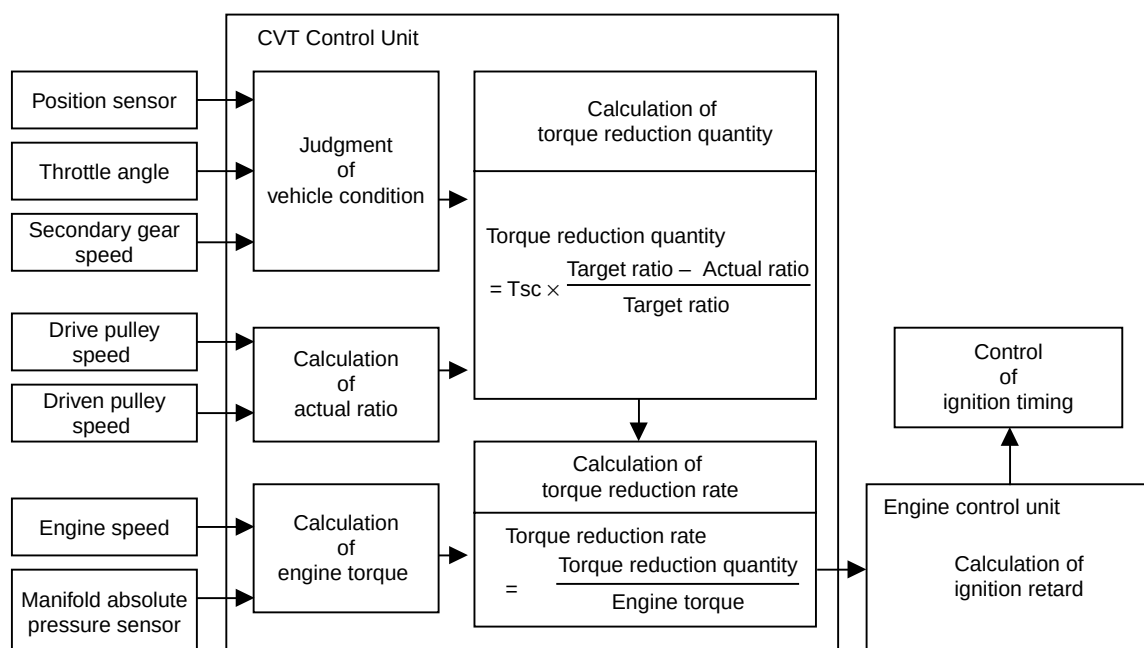


Fig.13 Control logic at reverse starting

condition, the torque reduction quantity is calculated from the actual ratio and the engine speed. This is compared with the conventional engine torque and the results are transmitted to the engine control unit as the torque reduction rate. The engine control unit determines the ignition retard timing from the torque reduction ratio and performs control to reduce the engine torque. This provides the same starting performance as the forward gears. Fig. 14 shows the change in each parameter during this process.

Performing the cooperative control described above made it possible to reduce both the weight and number of parts by adopting a single-pinion planetary gear without significant changes to the conventional system. Additional merits were an increase in creep force during reverse and lower noise.

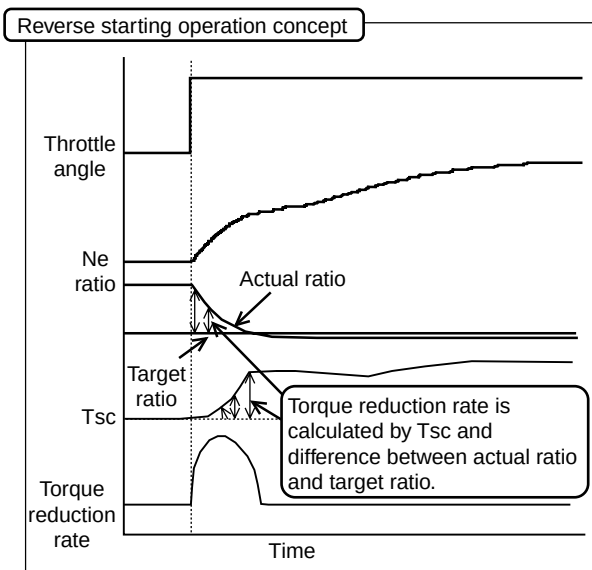


Fig.14 Reverse starting operation concept

5. Conclusion

The line pressure was reduced through a direct control system for pulley side pressures, friction was reduced by lubricant pressure switching control, etc., and shift control with a broad gear ratio was adopted. These measures helped to achieve a fuel economy of 32 km/l in the 10-15 mode, which is the top-level in Japan for automatic vehicles.

In addition, forward-reverse selection with a single-pinion planetary gear and other changes reduced the weight by 7% and the number of parts by 12% compared to the conventional CVT.

The technologies used in this CVT were developed for hybrid vehicles, but can also be used in CVT for conventional vehicles, and we are certain that we have developed a compact new CVT which will serve as the basic framework for CVTs in the 21st century.

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