Koyo's Approach to Continuously Variable Transmissions (CVT) for Automobiles

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Recently, a continuously variable transmission (CVT) is increasingly used with rapid speed.
It is because CVT attracts attentions as a device for low-emission and low- fuel economy vehicle. Also, CVT has a feature of smooth acceleration performance without shifting shock.
This paper presents the trends of CVT and a brief overview of full toroidal IVT that Koyo has been developing.

***Key Words**: CVT, IVT, toroidal, variator*

1. Introduction

Recently, the demand for reducing the burden on the global environment has increased significantly. Automakers are strenuously working on the reduction of exhaust gas and fuel consumption. They are pursuing weight reduction, miniaturization, more efficient driving systems and cleaner exhaust gas using lean-burn engines or catalytic converters. Other technologies, such as 42V power-supply, compact and highly efficient manual transmissions, automatic MT, multistage automatic transmissions, and continuously variable transmissions are also being developed. Among such techniques, the continuously variable transmission attracts much attention as an effective means for continually providing an engine operation with optimal performance, further improving fuel consumption and reducing emissions. The reason why the fuel consumption can be improved is that the continuously variable transmissions allow the change gear ratio to be selected freely and continuously, thus providing operation along an optimal fuel consumption curve having the highest engine combustion efficiency and they also provide expansion of a lockup region.

In general, continuously variable transmissions are mainly classified into mechanical, hydraulic and electrical type. Various systems have been developed for each type. However, a mechanical type continuously variable transmission is typically used in automotive applications.

This paper briefly describes the trends for mechanical type continuously variable transmissions (hereinafter abbreviated as CVT) for automobiles and also introduces the outline of an IVT variator, a subset of the CVT, which has been developed by Koyo.

2. Trends of CVT

As shown in **Table 1**, automotive CVT is mainly classified into a belt type and toroidal type. The belt type includes a metal V-belt type, dry hybrid belt type, and chain type, and is mainly used for an FF vehicle having an engine displacement of 2.8 liter or less. Most of belt CVTs practically used are metal V-belt type.

2. 1 Belt Type CVT

The CVT was first used in an automobile at the end of 19th century and a V-belt type was used. By 1958, the Dutch company, DAF, had manufactured more than one million rubber V-belt type CVTs (Variomatic) but could not improve the product due to technical limitations in the movement for a higher output engine. However, this experiment is said to have spurred the development of a chain type (Borg Warner) CVT or a metal V-belt type (Van Doorne) CVT. The Van Doorne metal V-belt is a push type belt, which differs from the chain type in that the drive side pushes the follower side to transmit power. This belt was introduced into the market for the first time when it was mounted in a Subaru JUSTY in 1987[1]. Subsequently, the Van Doorne metal V-belt has been used in many other types of vehicles and now constitutes approximately 10% of all automatic transmissions (hereinafter

Table. 1 CVT in automobile

	Belt CVT			Toroidal CVT	
	Metal V-belt	Dry hybrid belt	Chain	Half	Full (IVT)
Transmission torque, Nm	200～250	100 or less	300	380	600
Starting device	Yes	Yes	Yes	Yes	No
Engine applied	2.5 L or less	1 L or less	2L	3.5L	5.5L
Feature		No hydraulic apparatus required		Speed ratio control	Torque control

abbreviated as AT). For this reason, the year1987 can be said as the dawn year for technical establishment of CVT.

On the other hand, a chain type CVT was mounted in an Audi A4 which entered the market in 2001[2]. A currently-practiced metal V-belt CVT has the maximum transmission torque of 350N·m, whose value is now required to be significantly larger in order to be used in large vehicles. The chain type CVT has a possibility of providing larger torque capacity as compared to the metal V-belt type.

2. 2 Toroidal CVT

A traction drive CVT had been proposed far back in the past and was first developed for an automobile by GM in the 1930s. However, the realization of the traction drive CVT had to wait for remarkable progress in tribology and control technology. Specifically, the development of a traction fluid with relatively large friction coefficient, exploding the conventional concept, the advancement of EHL theory[3], and the development of a long-life bearing steel[4] were required.

The traction drive CVT developed for an automotive transmission is a toroidal one. Current toriodal CVT is a half toroidal CVT[5]. "Toroidal" means a donut-like three-dimensional shape. The toroidal CVT is so-called because a part of a curved surface at the inner side of two disks constitutes the shape. **Figure 1** shows an example of the structure of the full toroidal CVT.

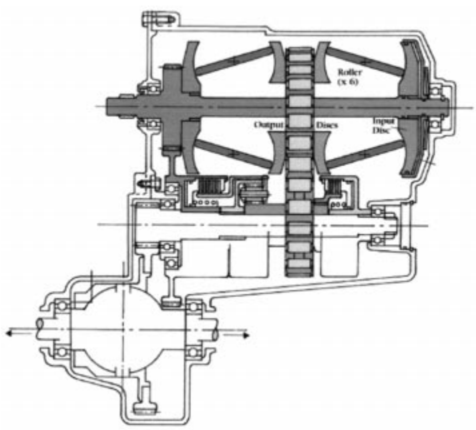

Fig. 1 Full toroidal IVT

The full toroidal CVT has a curved surface which is substantially similar to the toroid curved surface while the half toroidal has a curved surface which corresponds to a shape obtained by cutting half of the inner circumference of the toroid curved surface. Thus, in the full toroidal CVT, the roller sandwiched between the input and output disks has a disk shape. On the other hand, the roller of the half toroidal CVT has a hemispherical shape which is held by thrust bearing so as not to extrude from the disk. There is a difference between the full toroidal CVT and the half toroidal CVT in that the former has spin loss at the disk and the roller contacts while the latter theoretically has no spin loss. However, the half toroidal CVT has torque loss due to the thrust bearing. Thus, it is generally considered that the former and the latter substantially have the same efficiency as a transmission.

3. What is an IVT?

An infinitely variable transmission (hereinafter abbreviated as IVT) composing of a torque split using a planetary gear and a full toroidal CVT has been developed mainly by TOROTRAK LTD. in UK. It was reported[6] in 1993 that a vehicle equipping an IVT provides a 13% average improvement in the fuel consumption as compared to a vehicle equipped with a 5-speed MT according to the Corporate Average Fuel Economy (CAFE) method. Today, vehicles with IVTs exhibit a 20% improvement as compared to a 4-speed AT vehicle. The reason is that an engine control unit (ECU) selects an optimal gear ratio so that the engine always rotates efficiently, resulting in lower vehicle fuel consumption. Another reason is that CVTs, including a half toroidal CVT, use a speed ratio control, which requires a torque converter as a starting device while IVTs use torque control to eliminate the need for such a starting device, thus providing further improvement in fuel consumption due to the elimination of the loss associated with a torque converter.

IVTs are one of the ATs which provide continuously variable speed change over an extremely wide speed range. A normal AT provides a ratio range of about 4.5 and a belt CVT provides a ratio range of about 5.8 while IVT provides the ratio range from 0 to more than 3 under an overdrive condition, which means that IVT theoretically provides an infinite ratio range. This is why the modifier "infinitely" is used in the descriptive acronym 'IVT'.

4. Full Toroidal Variator

Koyo has developed a full toroidal type variator, the heart of an IVT. The variator is composed of double cavities and includes input and output disks, rollers, and hydraulic pistons for supporting the rollers, as shown in **Fig. 2**. The rollers sandwiched between the two disks provide a smooth and continuous variable speed change by freely selecting the inclined angle.

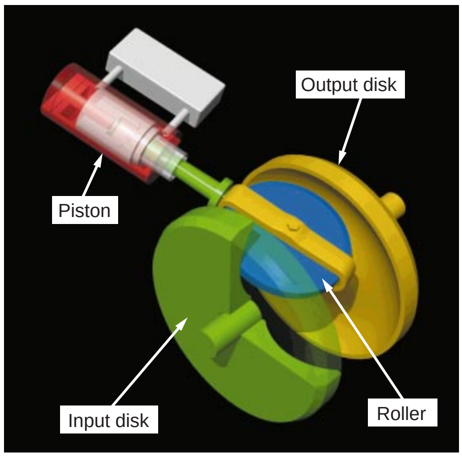

Fig. 2 Full toroidal variator

The IVT driveline is shown in **Fig. 3**. In **Fig. 3**, G represents a torque split gear, V represents a variator, E represents a planetary gear, and L and H represent clutches. The torque input from the torque split gear is transmitted from the input disk via six rollers to the pair of output disks. A hydraulic cylinder included therein, applies an end load to clamp the rollers in the contact region between the disks and rollers, which provides a highly efficient power transmission via the shearing force of the traction oil. The rollers also receive a reaction force caused by traction when transmitting the torque. Thus, each roller carriage end has a hydraulic cylinder to support the roller.

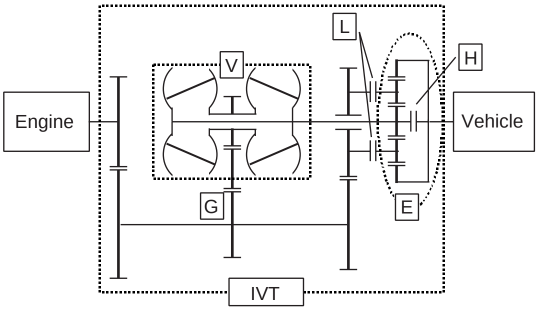

Fig. 3 Example of IVT configuration

4. 1 Traction Model

Changing speed is based on an autonomous mechanism utilizing the traction force. This mechanism was at last realized through the torque control, which varies the roller inclination depending on the torque. The variator requires high responsiveness to the speed change. It has been possible to model the relationship of the sliding contact between the disks and the roller and the traction coefficient via the Johnson-Tevaarwerk theory[7] to a variator assembly model. This model was used in a simulation to verify the variator's high-speed response and stability in various driving conditions[8]. The dynamic condition occurring at the contact area between the disk and the roller was confirmed to provide an optimal geometry. **Figure 4** shows an example of the simulated variator results.

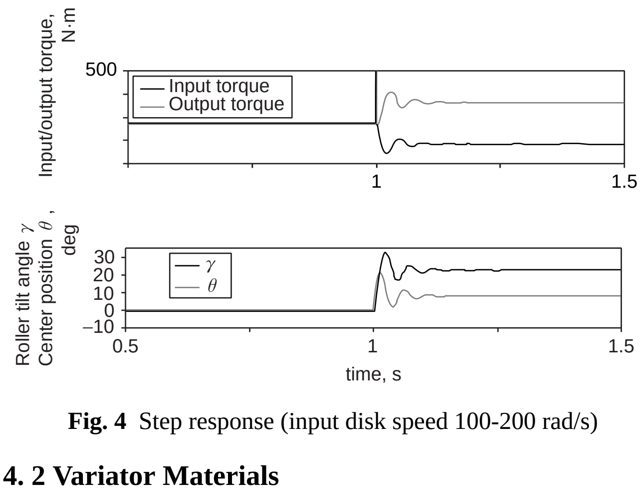

Fig. 4 Step response (input disk speed 100-200 rad/s)

4. 2 Variator Materials

When developing a variator, technological advancements in tribology, such as material development or EHL analysis, are essential. Such a technique is particularly important at the contact area between the disks and rollers of the variator for the transfer of power. The contact is loaded with the Hertzian pressure of 1 to 3.5 GPa and traction force under medium high temperature, thus requiring sufficient durability of the material. As the material for disks and rollers, KUJ7[4] developed by Koyo is used. KUJ7 was developed as low cost bearing steel nearly equal to high speed steel such as M50 or SKH4 and can be used under the medium high temperatures ranging up to 200℃.

The hardness of conventional bearing steel SUJ2 decreases under high temperature, and the service life, in turn, becomes shorter corresponding to the reduction of hardness. Under high surface pressure, the material may have undergone a structural change due to the internal shearing stress in the material. When such a structural change occurs in a region of high shear stress, which is called Dark Etching Area (DEA) or White Band (WB) as shown in **Fig. 5**, a crack may initiate and propagate to cause flaking.

KUJ7 is characterized by the addition of Si and Mo to provide superior resistance to annealing and structural stability is provided at medium high temperatures range by the stabilized carbide by the addition of Cr and Mo. **Figure 6** shows the microstructural changes of samples of KUJ7 and SUJ2 with 250℃ annealing when subjected to a rolling fatigue life test with an oil temperature of 150℃. The result was that the KUJ7 sample showed no structural change at seven times the number of stress cycles at which a structural change was evident in the SUJ2 sample, thus indicating that the KUJ7 sample has a stabilized structure. For reference, a comparison between the chemical composition of KUJ7 and SUJ2 is shown in **Table 2**.

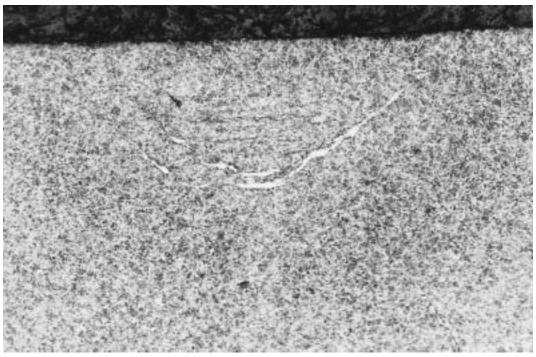

Fig. 5 Dark Etching Area (DEA)

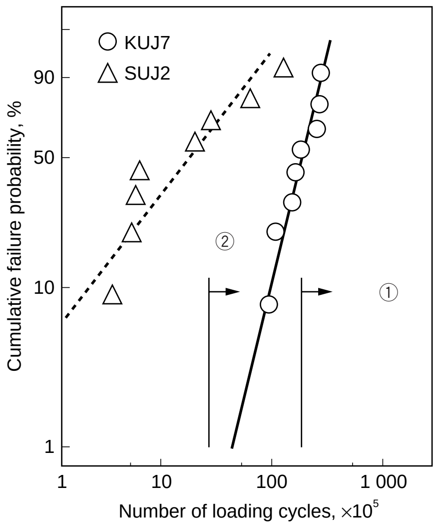

Fig. 6 Time-course changes of microstructure

Table 2 Main composition of the steel developed

mass%

	C	Si	Mn	Cr	Mo
KUJ7	1	1	0.5	2	0.5
SUJ2	1	0.2	0.3	1.5	–

4. 3 Life

Figure 7 shows the results of the durability test for KUJ7 disk and roller with an actual assembly test rig. This test utilized a power circulating and 4-square-type test rig and subjected the machine to operating conditions typical of an actual variator. The appearance of the test rig is shown in **Fig. 8**. Initially, the disks and rollers had either surface-initiated flaking or a crack on the raceway as shown in **Fig. 9**. This crack, generated at the boundary of the rolling mark of the rolling element to have an inclination of approximately 45° to the rolling direction, has a unique form which is not shown in the raceway surface of a rolling bearing. It was found that such a crack could be prevented by a countermeasure in which a compressive residual stress is applied to the material by shot peening. This phenomenon was clarified by stress analysis using Hanson's elasticity analysis solution to theoretically verify that the compressive residual stress is effective. **Figure 10** shows an example of the analysis results. As indicated in **Fig. 10**, the magnitude of the stress increases as the direction of the stress changes and the inside-surface shear stress value moves from the center of the rolling mark to the rolling mark boundary to have a value of 45°. It was also determined that the surface-initiated flaking can be prevented by providing an optimal surface roughness. The life of a component with a raceway surface processed to high precision is typically limited by internally initiated flaking due to rolling fatigue. In addition to the aforementioned countermeasure for surface damage, it was also found that an optimal material heat treatment provided improved rolling fatigue life allowing disks and rollers made with KUJ7 to achieve the desired durability[9], as shown by ● marks in **Fig. 7**. However, as in the case of ATs and CVTs, IVTs are also required to be smaller, resulting in the current challenge in which a smaller variator must transmit greater torque. Further improvement in life and mechanical strength is also required. Thus, Koyo is still working on improving the product design and developing longer life materials.

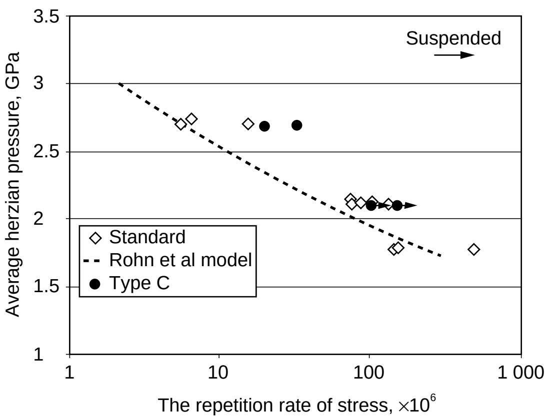

Fig. 7 S-N diagram[9]

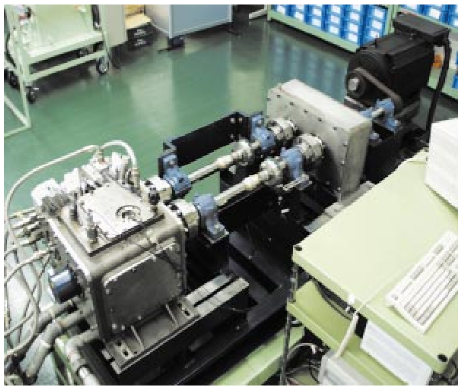

Fig. 8 Actual variator test rig

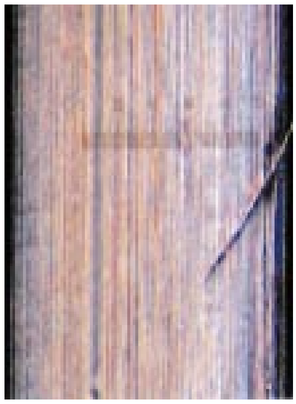

Fig. 9 Surface crack

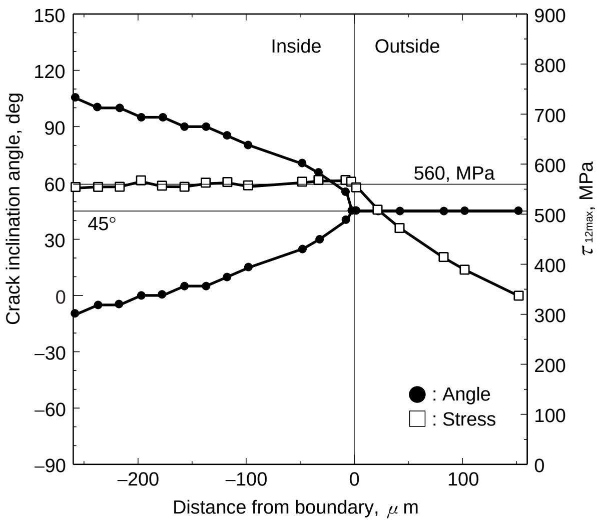

Fig. 10 Stress analysis result

5. Conclusion

The features of CVT which significantly contribute to energy savings, the reduction of CO_2, provision of smooth power transmission and the current development status of IVT variators are described. There are some expectations that vehicles equipped with CVTs will be the core of future automotive drivelines along with those for fuel-cell and hybrid vehicles. IVTs have a particular advantage over a conventional CVT as an IVT can provide larger torque capacity and thus can be used for larger vehicles. Koyo will do its best for further developing the technology for reducing the burden on the environment using tribology and high precision processing, which was established in rolling bearing development.

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