Dynamic Simulation Methodology of Half-toroidal IVT Variator System with Feedback Control

Toshihiro Saito

Honda R&D Co.,Ltd. Automobile R&D Center

Eiji Inoue

NSK Ltd.

Yoshitaka Tamoto

Idemitsu Kosan Co.,Ltd.

Abstract: *Dynamic simulation methodology of a half-toroidal IVT variator system using a traction drive was developed. The rheological properties of a traction fluid dependent on surface pressure, sliding velocity, and contact surface temperature were identified from four-roller test apparatus by considering Hertzian pressure distribution on traction surface. Since a half-toroidal CVT variator system was required to analyze simultaneously the vibration, deformation, and contact behavior, Abaqus/Explicit solver was used. Additionally, this approach provides arbitrary control of the variator speed ratio, a mechanical sensor-less control logic that combined a state estimation observer with feedback control was also coupled with the solver. These methods made it possible to quantify the torque capacity and power transmission efficiency of a half-toroidal variator, and also enabled visualization of the friction force spinning behavior on traction surface.*

Keywords: *Powertrain , IVT, Half- toroidal variator, Traction drive, Traction fluid, Glass transition, Mechanism , Assembly deformation, Interface friction , Connectors, Coupled analysis, User subroutine, Vuamp, Feedback control, Observer, Sensor-less, Transmission Efficiency, Dynamics, Vibration, Visualization.*

1. Introduction

Today's focus on environmental issues is intensifying demands for the realization of increased automotive fuel efficiency and reduced CO_2 emissions. As one response to these demands, internal combustion engines are being downsized in order to reduce friction. In the area of transmissions, it has become necessary to lower gear ratios at takeoff and increase gear ratios under cruise conditions in order to reconcile powerful drive force at takeoff with high fuel efficiency when the vehicle is cruising. As this implies, demand for wider ratio ranges is increasing.[(1)]

Fuel efficiency can also be increased by constantly changing the engine operating points to maintain the most advantageous state for fuel efficiency using metal V-belt CVT or chain CVT. In these cases, the ratio range can also be increased to around 7.0 by increasing the diameter of the pulleys. However, when the ratio range is increased by increasing the diameter of the pulleys, the transmission increases in size and weight. In addition, because power is transmitted by the friction force between the metal belt and the pulleys, increasing the transmission efficiency of the CVT itself is an issue.[2]

2. Half-toroidal IVT

The infinitely variable transmission, or IVT, is a transmission that makes it possible to further increase the ratio range.[3] IVT are termed "infinitely variable" because they allow the transmission output speed in relation to input engine speed to be set at zero.[4]

Figure 1 shows a cross-sectional diagram of a prototype IVT for a front-wheel drive automobile. A double-cavity half-toroidal variator is positioned on the main shaft, while a planetary gear set for power splitting and Low Mode and High Mode clutches for switching modes are positioned on the countershaft. Low Mode is mainly used when the vehicle is taking off or reversing; in this mode, a power circulation mechanism is able to amplify drive force.[5] High Mode is what is known as a direct mode; the power circulation mechanism is not used in this mode. The power is transmitted using traction fluid, the higher transmissible torque would be expected.[6] The better fuel consumptions are calculated in urban cycles, IVT can be considered an alternative transmission .[2]

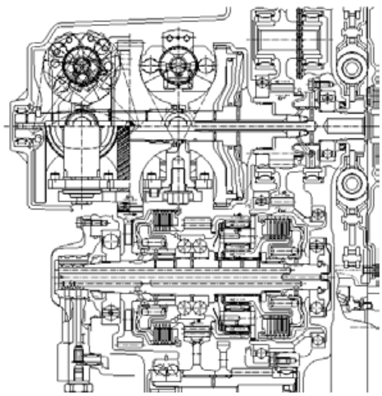


Figure 1. IVT for front-wheel drive vehicle.

3. Research Aims

The following three research aims were set in order to increase the accuracy of prediction of the torque transmission efficiency of a half-toroidal IVT:

· Formulation of a model for analysis of the behavior of a half-toroidal variator that considers elastic deformation

· Identification of the traction fluid friction characteristic using a four-roller test apparatus

· Introduction of gearshift and loader pressure controls to the model for analysis of half-toroidal variator behavior

4. Half-toroidal Variator Shift Mechanism

Figure 2 shows an external view of a half-toroidal variator. The power rollers are supported by trunnions, and are moved up and down by the differential pressure of the shift pistons. The trunnions are fitted to upper and lower yoke plates, and can also move in the direction of rotation. The power rollers rotate, sandwiched between input disks and output disks by loader piston pressure.[7]

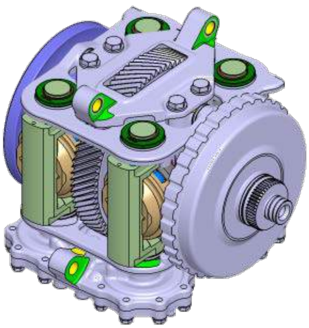
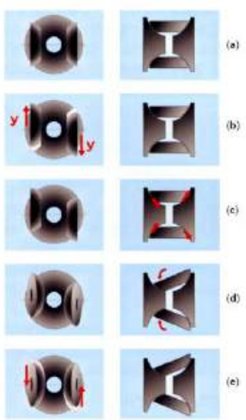


Figure 2. Half-toroidal variator.

Figure 3 shows the principle of operation of a toroidal variator.[8] When the axis of rotation of the power roller and the horizontal axis of the disk center correspond, the power roller does not tilt, and the ratio is constant. When the power roller is slightly offset in the y direction from this state, friction force is generated in the direction of tilting, the power roller begins a tilting motion, and the mechanism transitions to ratio shift. When the offset displacement y returns to its original position, the tilting motion stops at that point, and the ratio becomes constant.[9] As this indicates, by applying a slight offset displacement, y, it is possible to instantaneously change the ratio.



Reference：H. Machida, et al.: Development of the Half Toroidal CVT POWERTOROS UNIT, NSK Technical Journal No.669

Figure 3. Principle of shift control by half-toroidal variator.

Then, the speed ratio iv is derived from the following equation (1).

$$\mathrm{iv} = \frac{\omega in}{\omega out} \qquad (1)$$

ωin and ωout show the input rotational speed and the output rotational speed respectively (Fig. 4).

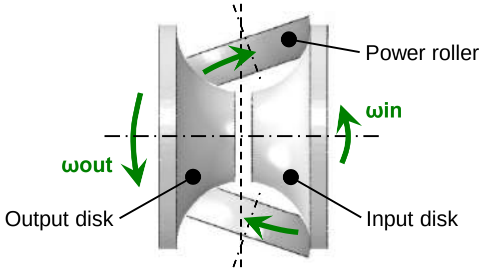


Figure 4. Changing rotational speed of half-toroidal variator.

4.1 Formulation of Model for Analysis of Behavior of Half-toroidal Variator

Figure 5 shows a model of a half-toroidal variator for analysis of the unit's behavior. Finite element models are used for each part in order to consider elastic deformation. To make it possible to use the traction coefficients identified using the four-roller test apparatus model, the mesh size for the traction surface was set equivalent to that of the roller surface in the four-roller test apparatus model. A predetermined clamping force was imparted to the power roller by imparting oil pressure to the loader pistons. Feedback control was applied to the clamping force and shift force on the power rollers based on the operating state.

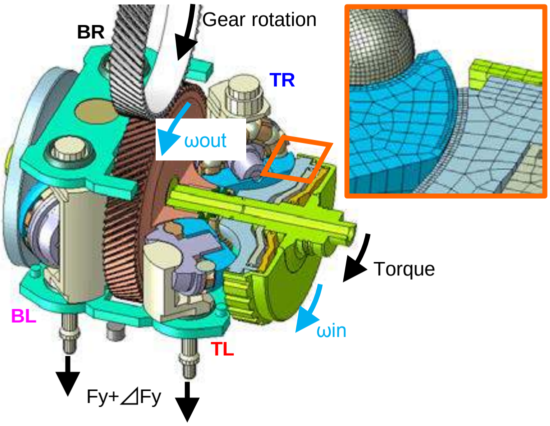


Figure 5. Toroidal variator model for analysis of behavior.

4.2 Identification of Traction Fluid Characteristic

A toroidal variator transmits power by means of the shear force of the traction fluid between the disks and the power rollers.

The four-roller test apparatus shown in Figure 6 was used in measuring the traction fluid characteristic.[10] The three outer rollers rotate at a constant speed; the slip rate can be changed by imparting a different speed of rotation to the center roller.

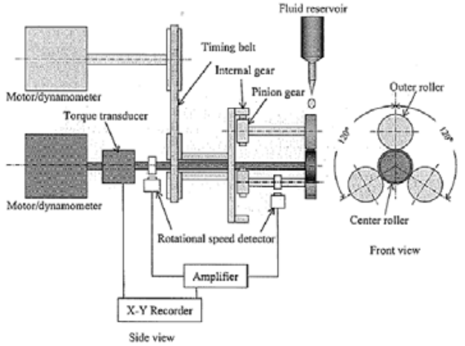


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Figure 6. Structure of the four-roller test apparatus.

Figure 7 shows examples of measurement results. The relationship between the difference in the speed of rotation of the rollers and torque when the outer rollers are pushed against the center roller at a constant load was studied. Changes in the temperature of the outer rollers were also measured.

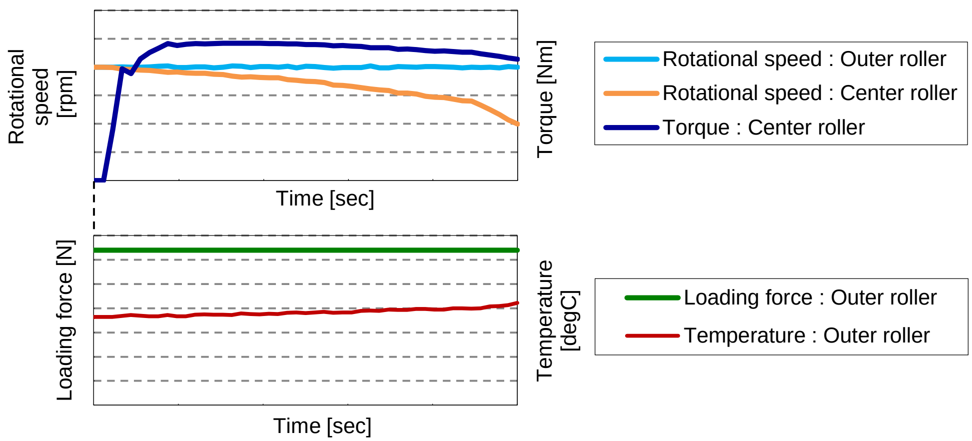

Figure 7. Four-roller test measurement results.

A traction characteristic for use in analysis of the behavior of the toroidal variator was determined based on the measurement results. Because the traction surfaces would be treated as a friction transmission model in the model for analysis of variator behavior, it was necessary to convert the shear force of the traction fluid into the friction force of the contact surfaces. A model for analysis of the behavior of the four-roller test apparatus, shown in Figure 8, was therefore formulated, and a traction characteristic that produced a torque response identical to that of the measurement results was identified. The generated model was treated as an elastic body, and the size of the mesh divisions was set to make it possible to reproduce the smooth rolling motion of the rollers. Figure 9 shows the calculated traction characteristic. The maximum traction value reaches around 0.3, this is because the calculation is based on the each point in the contact patch, not the conventional average value over the contact patch. The calculated characteristic reproduces the tendency for the traction coefficient to increase at high surface pressures, when the traction fluid undergoes glass transition.[11]

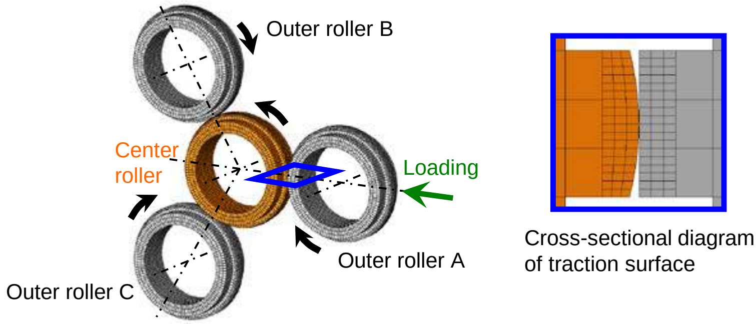

Figure 8. Model for identification of traction characteristic.

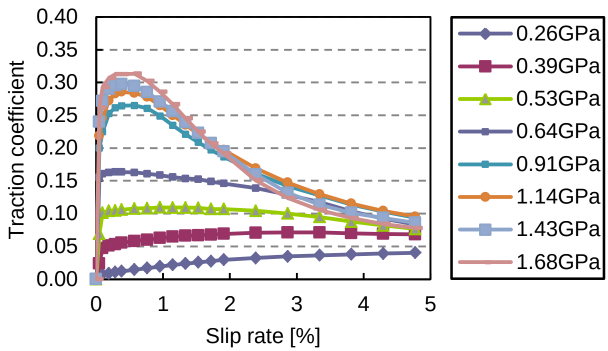

Figure 9. Identified traction characteristic.

4.3 Introduction of Shift Control and Loader Pressure Control

The tilting motion of the power roller is controlled by adjusting the offset displacement y. This offset produces an infinitesimal slip called sideslip, and this sideslip generates a tilting force. The speed of tilting is dependent on the offset displacement y, and on the geometric form and the angular velocity of the power roller. The variator can be accelerated and decelerated by making the offset displacement y positive or negative. The offset displacement y is controlled by adjusting the differential pressure of the shift pistons.[12]

Figure 10 shows the block diagram used in ratio control for the half-toroidal variator. The controller is made up of ratio deviation feedback and offset displacement y feedback. Feedback of the offset displacement y is sensor-less, using an estimated value as an observer.[13] The controller is implemented to the finite element analysis solver, using User-subroutine Vuamp in the solver function.

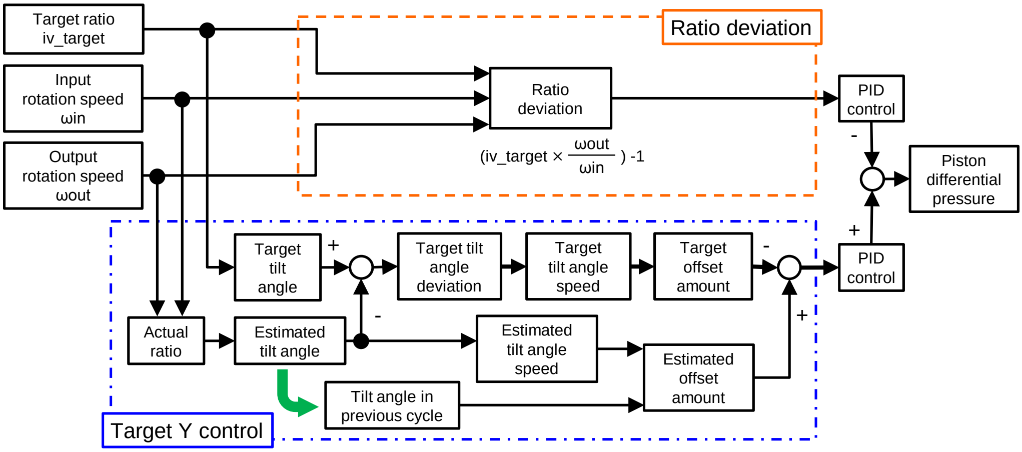

Figure 10. Speed ratio controller.

5. Results of Analysis of Behavior of Half-toroidal Variator

An analysis of the behavior of the half-toroidal variator was conducted using the combination of the traction characteristic shown in Figure 9 and the ratio controller shown in Figure 10 in the toroidal variator model for behavior analysis shown in Figure 5.

5.1 Relationship between Ratio and Offset displacement y

Figure 11 shows the actual ratio and the results of calculation of the behavior of offset displacement y when shift was conducted to reach the target ratio. The offset displacement y is basically identical for the four power rollers, and returns to close to zero when shift is completed.[14] In addition, displacement y increases in the transition from a shift in which the rate of change of the target ratio is high to a steady state. This indicates that the ratio shift control introduced into the model for analysis of the behavior of the half-toroidal variator is functioning as intended.

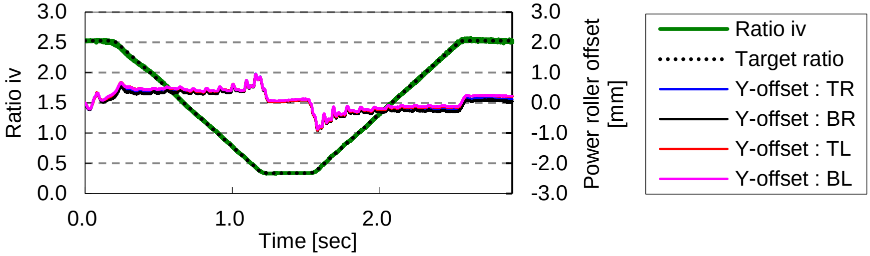

Figure 11. Effect of speed ratio controller.

5.2 Accuracy of Prediction of Half-toroidal Variator Transmission Efficiency

The transmission efficiency of a half-toroidal variator was predicted using the developed method. Figure 12 shows a comparison of prediction results and measurement results. Operating conditions were Nin=1000 rpm and Tin=200 Nm for each ratio. The loader pressure was controlled to produce a variator M value of 0.06.

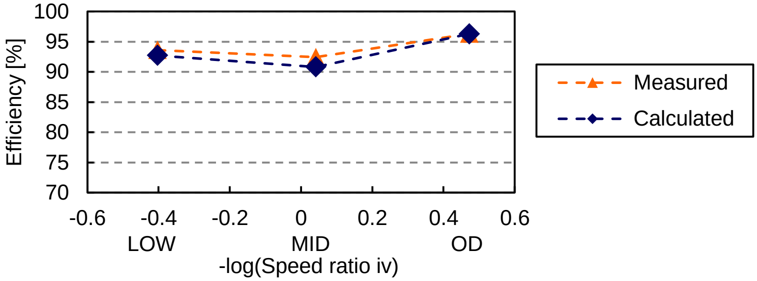

Figure 12. Results of prediction of variator efficiency.

Figure 13 shows the apparatus used in measurements of transmission efficiency. The accuracy of the predicted values for transmission efficiency is within ±2%, and the changes in transmission efficiency in response to the ratio were also predicted accurately.

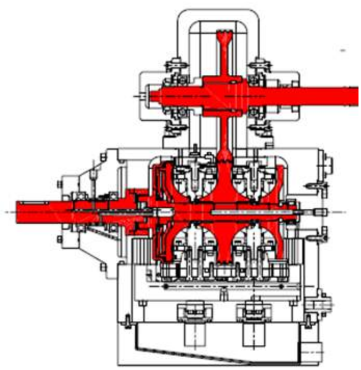

Figure 13. Measurement apparatus of variator efficiency.

And this is because the ratio of friction force vectors on the traction surfaces other than in the direction of torque transmission is at its maximum in MID ratio and at its minimum in OD ratio (Fig. 14).

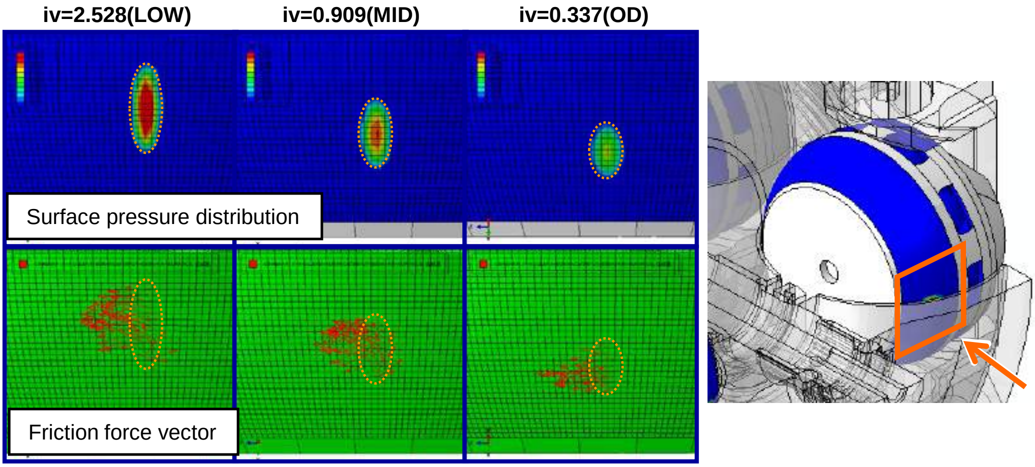

Figure 14. Surface pressure distribution on traction surface and friction vector.

6. Conclusion

· A finite element analysis solver was used in order to make it possible to consider elastic deformation of the half-toroidal variator and treat dynamic contact friction. It was possible to treat the spin of the friction force vectors produced on the contact surfaces quantitatively by setting the same mesh size for the traction surfaces as that for the model used for analysis of the behavior of the four-roller test apparatus.

· A model for analysis of the behavior of a four-roller test apparatus was formulated, and a traction fluid characteristic making it possible to reproduce measured torque under multiple simulation conditions was identified. This characteristic was a function of surface pressure, slip speed, and temperature, values increased when the friction fluid underwent a glass transition in its solid phase.

· The accuracy of prediction of the transmission efficiency of the half-toroidal variator was within ±2%, and the changes in transmission efficiency in response to the ratio were also predicted accurately.

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