

Review

Basic Analysis Towards Further Development of Continuously Variable Transmissions (Overview)

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Abstract

Various types of transmissions, representing a wide range of opinions, have been proposed worldwide. The CVT (Continuously Variable Transmission), which made its first appearance about 20 years ago as an ideal transmission, has also required considerable development in order to be ready for competitive dominance. This paper discusses the role of the CVT in the automotive power train, outlines areas requiring future technical development, and provides an overview of the research activity in our laboratories.

Keywords

CVT, Transmission, Belt, Traction drive, Efficiency, Power loss

1. Introduction

About 20 years have been passed since the Continuously Variable Transmission (CVT) became practical as a transmission for automobiles.^{1, 2)} During this period, stricter regulations on automobiles have required technological solutions for environmental concerns such as global warming and the reduction of CO₂ emissions while, at the same time, consumers have sought greater driving enjoyment from greater power output and responsiveness. Meeting this demand has led to the development of various expansive forms of the transmission, which converts the power of an engine to driving force, in addition to the CVT. This diversification has been growing. For example, most of the multistep Automatic Transmissions (AT) available until 2000 were, maximally, five-speed transmissions, but in the 2000s, the number of shifting gears has increased rapidly to 6 or 7 speeds, ratios are wider, and the transmissions are compact and light weight. Predictions are for this trend to continue.³⁻⁵⁾ The Automated Manual Transmission (AMT) has been successfully revived in, especially, the European market after a lapse in the trend toward automation and is now advancing to a model that has a mechanism for obviating power interruptions.⁶⁻⁸⁾ Another example of diversification is the hybrid system, which is promising as a powerful means of reducing CO₂ emissions, has an electrical/mechanical transmission mechanism that mainly includes motors. This system has practical uses as an important mechanism for power regeneration and power assist as well as power transmission using the continuously variable mechanism⁹⁾ with two mortors and one planetary gear set.

The CVT as a means of providing a continuously varying gear ratio has been developed with the basic aim of increasing transmission torque capacity. The capacity of a push-belt CVT has increased from 100 Nm at the initial stage to a current 350 Nm.^{10, 11)} A chain-type CVT has been developed and provides capacity similar to that of the push-belt CVT.¹²⁾ In addition, a CVT with a traction drive system different from that of a belt system is starting to be used, and its capability to change speeds quickly gives it an advantage over the other types of

systems.^{13, 14)}

A look at the fundamental roles of the transmission confirm that these remain the transmission of the output of an engine to tires without loss, actuation of the engine at an optimum point of its thermal efficiency and its emission as the greatest actuator in the engine, and the offering of smoothness and responsiveness that is satisfying to drivers. As the hybridization trend continues, the fusion of the mechanical transmission and the electric motor will be necessary.

Against this background, greater progress during the next 20 years than that achieved in the past 20 years will be required to extend the value of the CVT as an ideal transmission. Specifically, just as the AT improved its gear train by moving towards miniaturization, the CVT will need to challenge maximum limits as a machine capable of continuously varying the gear ratio. Our goals, though general regarding demand, are the achievement of the highest transmission efficiency and torque capacity, as well as an increase in gear ratio range and improved speed of ratio changes. We must also improve layout flexibility in response to the trend toward compactness and light weight.^{2, 15)} To meet these requirements, it is not enough to redesign known mechanisms. Rather, the key resides in reconsidering the basis of the power transmission mechanism and developing new ideas from that reconsideration. In this special issue, therefore, we will introduce a part of our investigation on the modeling of the power transmission state, force analysis, and measurement techniques from the point of view grasping basic power transmission phenomenon.

2. Basic CVT issues

In this section and the next, we will present the basic CVT issues and outline our investigations into these problems.

Generally, two types of CVTs are now manufactured for use in automobiles: the belt type and the traction drive type (**Figs. 1 and 2**). As forementioned the belt-CVT consists of two types of belts, a push system and a pull system, both of which transmit power by friction force between solids at the contact surface of pulleys and a belt

sandwiched between the pulleys. A traction drive CVT uses a mechanism that transmits power by shear force generated within a special oil sandwiched between two rolling elements.

Unlike the case of gears, power transmission in CVTs, superficially permitting a slight slide between the transmitting members, permits the movement in a direction different from the transmitting direction and the construction of a mechanism capable of continuous shift movement. The offsetting disadvantage of this system is that transmission performance is adversely affected. Consider these concepts using Eq. (1), which is a basic relationship representing a torque capacity T .¹⁶⁾

$$T = \mu \cdot F \cdot R \quad \dots\dots\dots(1)$$

where μ is a friction coefficient or a traction coefficient, F is an acting normal force to a tangential line direction on a transmitted surface, and R is a radius of the contact portion that is capable of varying a speed ratio. The μ defined here, as shown in Fig. 3, is represented as a function

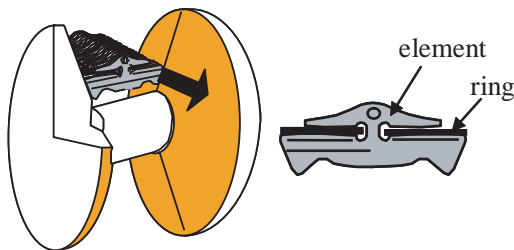


Fig. 1 Belt type CVT.

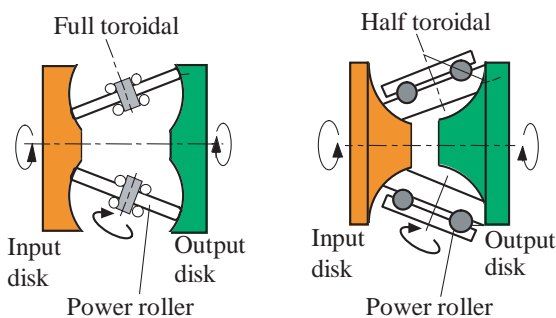


Fig. 2 Toroidal type CVT.

of sliding speed and a sliding ratio.

As readily supposed from Eq. (1), it is necessary to increase any one of μ , F and R or any one in combination with the others to increase the torque capacity T . In the case here, it is not easy to increase the pressing force F because more power is needed to generate the force and a heavier burden such as mechanical strength, wear, and the like is placed on the members constituting the continuously variable mechanism namely variator. The increase of the radius R causes the size of the whole mechanism to be larger and works against the recent need for compactness and light weight. Accordingly, increasing μ is the major key to higher performance, although it is not easy to develop a fluid or a friction material that can attain a sufficiently high value of μ in view of durability and working environment problems. As a result, known CVTs are the product of development that carefully balances μ , F and R as a whole with gradual modifications.¹⁷⁻²⁰⁾

The reduction in contact loss where power is transmitted and received and in loss among the internal elements of the variator, and the minimization of the actuator power for generating the pressing force F are required to increase transmission efficiency. Because all the speed components in the direction other than the tangential line on the contact surface become loss, it is necessary to create a transmission structure that does not cause such loss to occur. Losses among the elements within the variator include friction loss and operational loss caused by forces exerted between the constituent members. These losses depend largely on the type of the variator mechanism, and the view point for reducing such losses, in addition to contact loss, is to analyze the operation of the

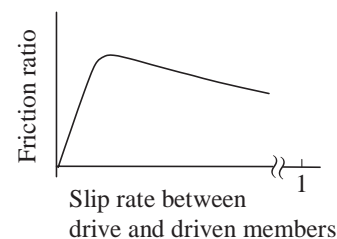


Fig. 3 Friction characteristics.

variator not only statically but also dynamically. The normal force and friction characteristics relative to the power transmission have a closely integrated relationship. Therefore, the clearer the friction characteristics, the easier it is to optimize the power required for generating the pressing force. Since it can be said that there are some aspects on which the results of analysis can have a positive effect on performance improvement, many manufacturers are trying to reflect these gains in products.²¹⁻²⁵⁾

3. Investigations in our laboratory

A remarkable improvement in performance might be achieved if we could overcome the basic problems and contradictory relationships pointed out above. As a basic process, the first thing we need to do is to make the physical phenomenon clear again. In our analysis, we pay attention to the relationship of the acting force between the constituent elements and the whole of the mechanism and to the friction force as a transmission force and as a loss, and place importance on the establishment of a physical model. In the first article, we will follow such a process to make a simple model of pulley deformation and the influence of excessive play as a part of our analysis for internal acting forces in push-belt CVT. This model will be used to explain the mutual action forces between the belt and the pulley. In the second article, we will propose a model of generation of the transmission friction force of a belt and consider the friction characteristics and the state of power transmission. In the third article, we will introduce a method for acquiring verification data required in the first and second articles and a method for determining signals as a means of substitution under conditions in which measurement signals are subject to restrictions. In the fourth article, we will explain the practical modeling of power transmission characteristics of the special oil used in a traction drive.

Although this special issue is a report that focuses only on the basic analysis of phenomena, we are beginning research on a mechanism that will increase the friction force and the traction force to improve performance. The point of our investigation regarding these matters is to understand the physical phenomenon at the interface

of the power transmission at a nano-order level. We have already acquired some interesting results from this investigation,²⁶⁾ but will leave these for the next report about the tripololy.

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