

Improvement of Transmission Efficiency in CVT Shifting Mechanism Using Metal Pushing V-Belt

Taiki Ando, Tooru Yagasaki, Shuji Ichijo, Kyohei Sakagami, and Soichiro Sumida
Honda R&D Co Ltd

ABSTRACT

Pulley thrust control, changes in the trajectory of the belt as it winds around the pulleys, and the amount of friction transmission were focused on in order to reduce transmission loss and increase the transmission efficiency of CVT. In the case of pulley thrust control, making use of the linear relationship between the rotary speed fluctuation transfer characteristic and the torque transmission capacity between the pulleys and the belt, it was possible to reduce the excess safety factor of the torque transmission volume. Due to pulley tilt, the trajectory of the belt displays deviations with the theoretical geometrical winding radius. The structure of the pulleys was modified in order to reduce this deviation and increase transmission efficiency. Optimization of the additives in the CVT fluid increased the coefficient of friction, decreasing pulley thrust and increasing transmission efficiency. At the same time, the application of a carbonitriding and a zinc electric discharge coating to help prevent wear in the parts of the belt elements and pulleys making contact balanced a high coefficient of friction with wear resistance.

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1. INTRODUCTION

The use of hybrid systems and CVT using metal pushing V-belts in automotive powertrains is becoming more widespread today from considerations of increasing fuel efficiency and reducing exhaust emissions. However, it has been indicated that increasing transmission efficiency during high-speed cruising is an issue for CVT using metal pushing V-belt[1]. The main factor in transmission loss in metal pushing V-belts is thought to be friction loss due to slipping. If this friction loss could be reduced, it would be possible to achieve further increases in fuel efficiency. In addition, reports indicate that it is possible to increase the efficiency of the belts by optimizing pulley thrust[2], and that deviation of the winding diameter of the belt from the theoretical winding diameter is a factor in reducing belt efficiency[3], suggesting that there is potential for increasing the efficiency of metal pushing V-belts. The research discussed in this paper focused on friction loss due to slipping in metal pushing V-belts, and in an attempt to increase transmission efficiency, studied a configuration that would reduce pulley thrust and help to control pulley tilt. This process produced findings regarding improvements that would help enable metal pushing V-belts to display sufficient levels of performance. This paper presents an overview of the research.

2. DEVELOPMENT GOALS

Metal pushing V-belts are made up of two sets of multi-layered rings and several hundred elements (Figs.1 and 2). Running between a fixed pulley and a movable pulley, they transmit drive force by means

of friction of the V-surfaces. While transmitting drive force, the belt is affected by the clearance between the elements, the elastic deformation of the elements, and the inclination of the pulley V-surfaces, resulting in micro slip between the pulleys and the elements in the direction of rotation and the radial direction. In addition, because the element pitch radius and the ring pitch radius are different, a difference in path is generated between the elements and the rings, and with the rotation of the pulleys, the slippage occurs. Similarly, because the pitch radius of the rings differs due to their thickness, differences in path result in slippage between the layered rings. Reducing ring tension, which generates a contact load, is an effective way of reducing friction loss due to slippage between the rings, and ring tension can be reduced by reducing pulley thrust. In addition, because slippage between the elements and the pulleys in the radial direction results from misalignment of the belt trajectory due to the tilt of the pulley V-surfaces, the slippage of the elements in the radial direction could be reduced by restraining the tilt of the pulley V-surfaces. The research discussed in this paper sought to increase the unit efficiency of the belt in the OD ratio, which is frequently used during cruising in actual vehicles. Seeking to realize a 3% increase in the unit efficiency of the belt, the project conducted research on a new pulley thrust control method, increasing the coefficient of friction, and restraining the tilt of the pulley V-surfaces. Here, the rate of increase in transmission efficiency will be defined as the difference between the efficiency of the conventional technology and the developed technology with the unit efficiency of the belt when transmission loss is zero as 100%.

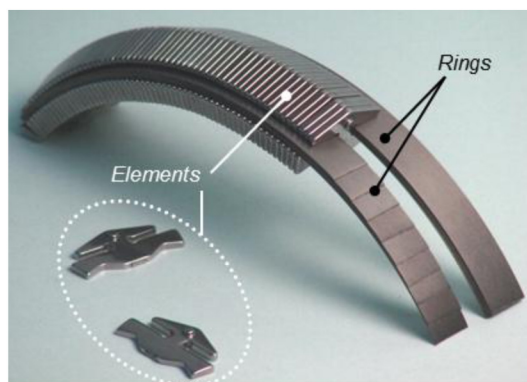


Figure 1. Metal pushing V-belt

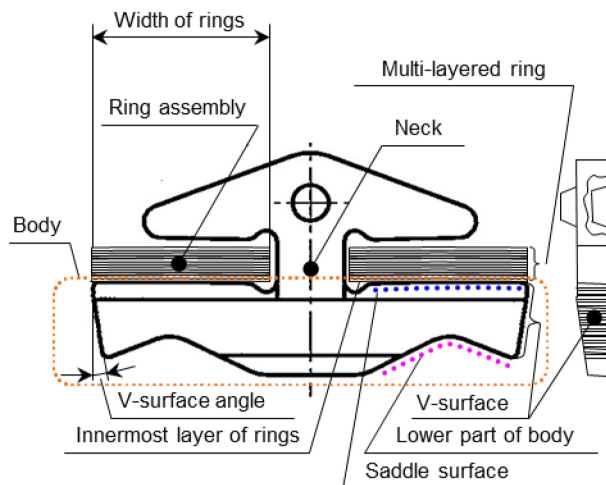


Figure 2. Configuration of elements and ring assembly

3. METHODS OF INCREASING TRANSMISSION EFFICIENCY

Lower pulley thrust determines the transmission capacity and higher pulley thrust determines the speed ratio, and depending on driving conditions, they can be applied to either the input or the output pulley. Lower pulley thrust consists of the thrust that is necessary for torque transmission, as determined by the angle of the V-surfaces, the winding radius, and the coefficient of friction, in addition to a level of thrust that considers the safety factor in view of belt slip. High-efficiency operation can be realized by reducing this safety factor to the minimum value. Conventional control considers variations in control hydraulic pressure against estimated input torque and calculates pulley thrust with consideration of the safety factor using a correction coefficient, in order to impart a pulley thrust that is more securely on the safe side against belt slip during operation. The new pulley thrust control method detects the margin against belt slip and controls pulley thrust with a desired margin as a target value, making it possible to operate the belt with the minimum necessary pulley thrust. In order to increase the coefficient of friction between the pulleys and the belt, additives were employed to modify the characteristics of the oil. At the same time, a zinc electric discharge coating treatment was applied to the pulley V-surfaces in order to help restrain the increased wear that would result from an increase in the coefficient of friction. The trajectory of the belt when winding around the pulleys deviates from the theoretical winding radius due to

the inclination of the V-surfaces. It was considered that because the configuration of the conventional movable pulley was such that the majority of pulley thrust was concentrated on the inner periphery, when the belt winding radius was tending towards larger diameters, the inclination of the V-surfaces would increase. The configuration of the pistons was modified and the balance of pulley thrust on the inner and outer peripheries of the pulleys was optimized, helping to restrain the inclination of the pulleys and reduce the amount of deviation of the belt trajectory.

3.1. New Pulley Thrust Control

With the torque ratio, T_r , the ratio between input torque, T , and the maximum amount of torque able to be transmitted, T_{max} , as an indicator, a coefficient of correction was determined from the difference between the torque ratio set as a control target value and the actual torque ratio measured in the vehicle, and a new control method that determines pulley thrust based on this coefficient was developed. The transmission efficiency of metal pushing V-belts displays a linear relationship with the torque ratio, and an increase in the torque ratio results in an increase in transmission efficiency, with an associated increase in micro slip. Efficiency is at its maximum when the torque ratio is close to 1; when the ratio exceeds 1, significant slippage that damages the belt occurs, and efficiency declines (Fig. 3). With an increase in the torque ratio, fluctuations in engine speed produce an increase in micro slip, resulting in damping of vibration energy and phase lag, which are transmitted by the belt. Using this relationship between the torque ratio and the transmission characteristic, it is possible to detect the torque ratio during operation and control it to the desired level.

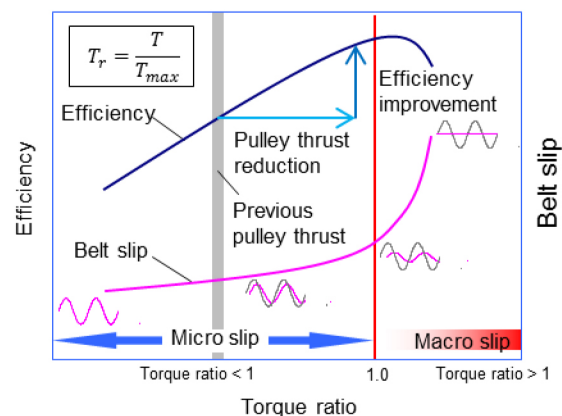


Figure 3. Relationship between torque ratio and efficiency

3.1.1. Detection of Torque Ratio

Making use of the fact that engine speed fluctuates during the ignition cycle, torque ratio detection determines the amplitude ratio or the phase lag from the speed fluctuation of the input shaft and the output shaft, and uses the correlation between the transmission characteristic and the torque ratio to determine the torque ratio. The present research used existing engine speed sensors, which powertrains are provided with for monitoring of engine speed in actual vehicles, to detect engine speed. The speed of the input and output shafts was measured using the output of the engine crankshaft speed sensor for the detection of the speed of the input shaft, and using the output of

the driven pulley shaft speed sensor for the detection of the speed of the output shaft (Fig. 4). The basic frequency of engine speed fluctuations was calculated from the ignition cycle, and the input shaft speed signal and the output shaft speed signal were used, respectively, to determine the amplitude ratio and the phase lag using a two-phase lock-in amplifier (Fig. 5). The relationships between the torque ratio and the amplitude ratio and between the torque ratio and the phase lag were studied experimentally, and it was found that phase lag increases linearly with increase in the torque ratio across the entire input frequency range. By contrast, the amplitude ratio does not increase linearly with increase in the torque ratio at input frequencies of 55 Hz and below. The results discussed above indicated that phase lag was the appropriate parameter for the detection of the torque ratio (Fig. 6). A three-dimensional map of phase lag, frequency, and torque ratio was formulated for use in vehicle control (Fig. 7).

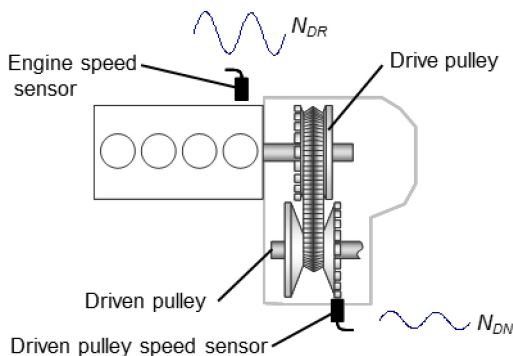


Figure 4. Rotary speed detection system

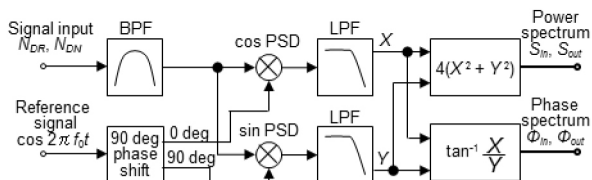


Figure 5. Two-phase lock-in amplifier

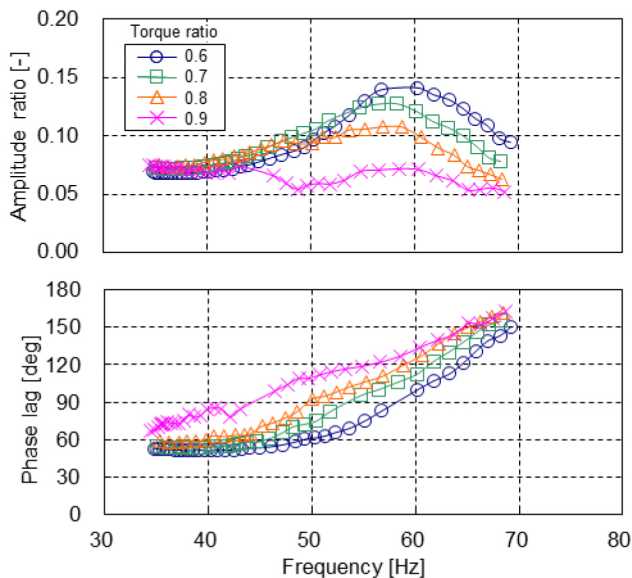


Figure 6. Amplitude ratio and phase lag

3.1.2. Application of New Pulley Thrust Control in Vehicle

The system switches from the conventional control specifications to new pulley thrust control under the condition that has been preset for switching to the new control; under other conditions the system returns to conventional control. The condition for application of the new pulley thrust control is when the belt speed ratio is in OD ratio, which is frequently used when a vehicle is cruising. The calculation of pulley thrust in the conventional control method considers belt slip and adds a certain amount of pulley thrust to the pulley thrust necessary for torque transmission as a safety margin. The new pulley thrust control method determines the actual torque ratio from the running state of the vehicle and the three-dimensional map, and calculates a coefficient of correction for the margin from the discrepancy between the target torque ratio and the actual torque ratio. When it has switched from conventional control to new pulley thrust control, the system substitutes the corrected margin for the conventional control margin and calculates pulley thrust. The application of new pulley thrust control has increased the torque ratio from 0.45 to 0.7 and reduced pulley thrust by approximately 40% against the conventional control method when cruising in OD ratio (Fig. 8).

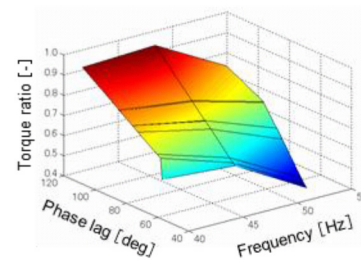


Figure 7. 3D torque ratio map

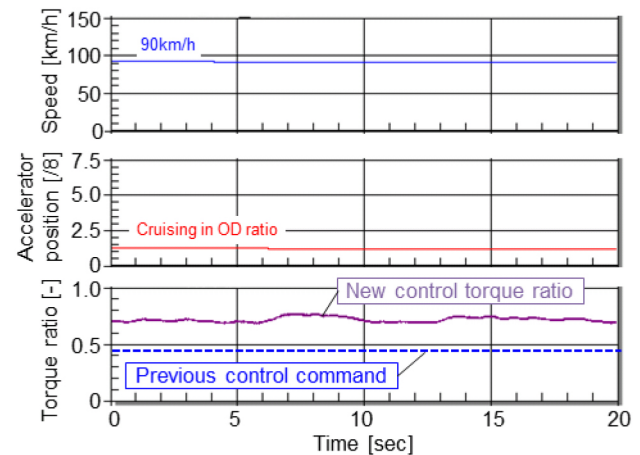


Figure 8. Test results for new pulley thrust control

3.2. Method of Increasing Coefficient of Friction

The transmission of drive force between the pulleys and the elements occurs as a result of friction force generated by shear of the boundary film, which is a reaction film produced by additives in the CVT fluid (Fig. 9). In order to increase the coefficient of friction, it is necessary to increase the shear strength of this boundary film. The research experimented with additives with the aim of increasing the coefficient of friction in order to realize a reduction in pulley thrust against the conventional value. Sliding tests were conducted using