

Study of High-efficiency CVT Shifting Mechanism Using Metal Pushing V-belt

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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 carbonitride heat treatment 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.

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-belts⁽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 modifications 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 belts are 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

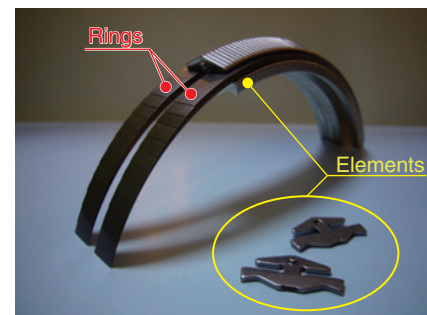


Fig. 1 Metal pushing V-belt

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difference in path is generated between the elements and the rings, and with the rotation of the pulleys, this results in slippage. 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 controlling 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 controlling 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%.

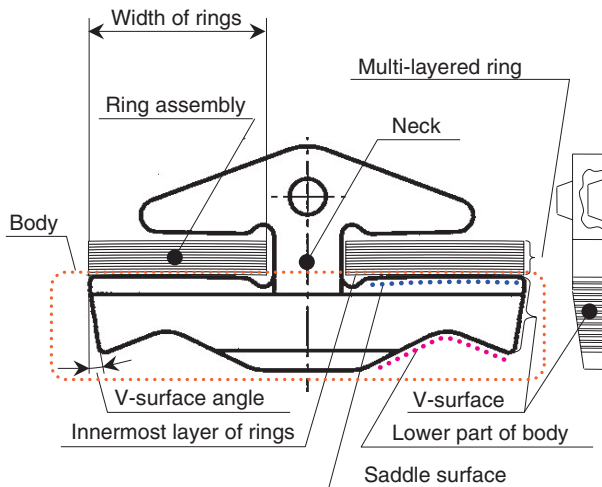


Fig. 2 Configuration of elements and ring assembly

3. Methods of Increasing Transmission Efficiency

Low pulley thrust determines the transmission volume and high pulley thrust determines the shift ratio, and depending on driving conditions, they can be applied to either the input or the output pulley. Low 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 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 pulley 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 control 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 control 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.

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 power spectrum ratio or the phase difference 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 changes was calculated from the ignition cycle, and the input shaft speed signal and the output shaft speed signal were used, respectively, to determine the power spectrum ratio and the phase difference using a two-phase lock-in amplifier (Fig. 5). The relationships between the torque ratio and the power spectrum ratio and between the torque ratio and the phase difference were studied experimentally, and it was found that phase difference increases linearly with increase in the torque ratio across the entire input frequency range. By contrast, the power spectrum ratio does not increase linearly with increase in

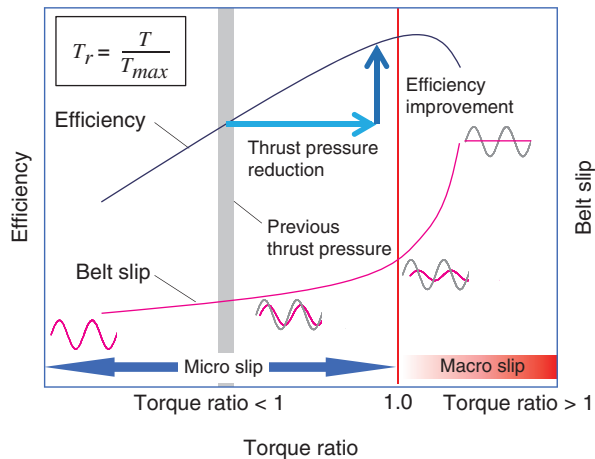


Fig. 3 Relationship between torque ratio and efficiency

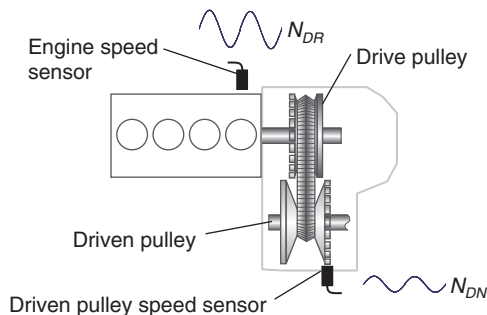


Fig. 4 Rotary speed detection system

the torque ratio at input frequencies of 55 Hz and below. The results discussed above indicated that phase difference was the appropriate parameter for the detection of the torque ratio (Fig. 6). A three-dimensional map of phase difference, frequency, and torque ratio was formulated for use in vehicle control (Fig. 7).

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

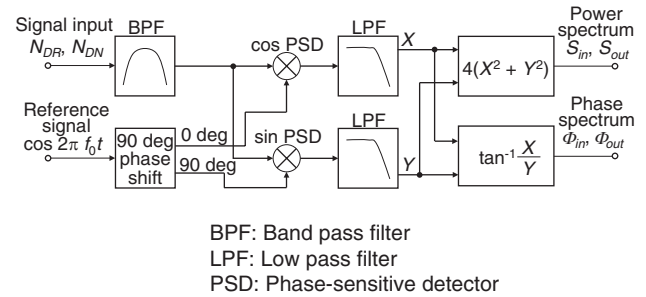


Fig. 5 Two-phase lock-in amplifier curve

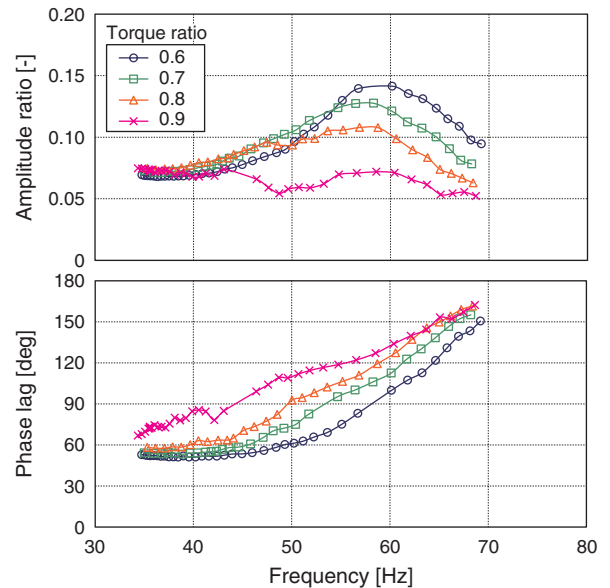


Fig. 6 Amplitude ratio and phase delay

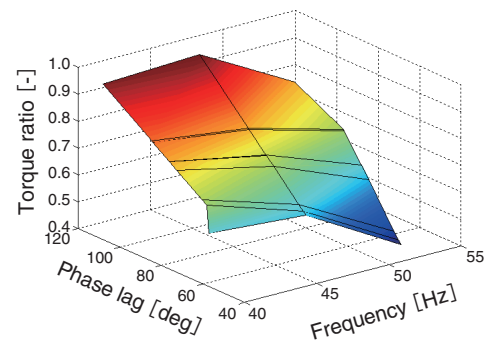


Fig. 7 3D torque ratio map

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 control is when the belt shift ratio is the 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).

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

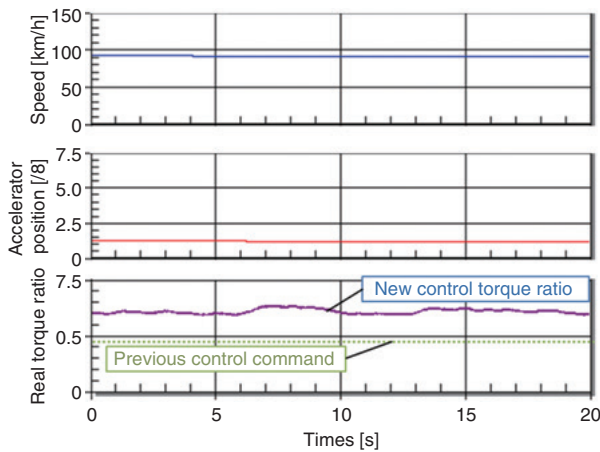


Fig. 8 Test results for new pulley thrust control

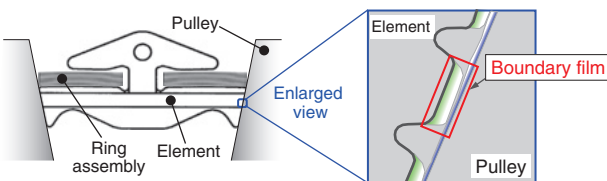


Fig. 9 Principle of frictional force

the coefficient of friction in order to realize a reduction in pulley thrust of 10% against the conventional value.

Sliding tests were conducted using CVT fluids of differing coefficients of friction, and the metallic structures of the sliding parts were examined. It was found that the depth of the micro-crystallizing metal structure close to the surface of the sliding parts increased with an increased coefficient of friction (Fig. 10). In addition, cracks appeared at the boundary between the normal metal structure and the micro-crystallizing metal structure, and peeling occurred (Fig. 11). When increasing the coefficient of friction, it would therefore be necessary to control the generation of a micro-crystallizing metal structure and attempt to prevent peeling wear.

3.2.1. Formulation of additive

The coefficient of friction between the pulleys and the elements is affected by the belt shift ratio and temperature. With regard to the temperature characteristic, the temperature at which the friction-modifying agent (FM agent) in the CVT fluid is activated differs depending on the type of FM agent used. The research therefore selected the FM agent and adjusted ratios in order to minimize the reduction in the coefficient of friction at low temperatures. With a phosphorous-based extreme-pressure agent as the main ingredient, a cleaning agent and a dispersant were added in order to produce an FM agent created with consideration of belt noise and the clutch characteristic. The coefficient of friction at the temperature used as the

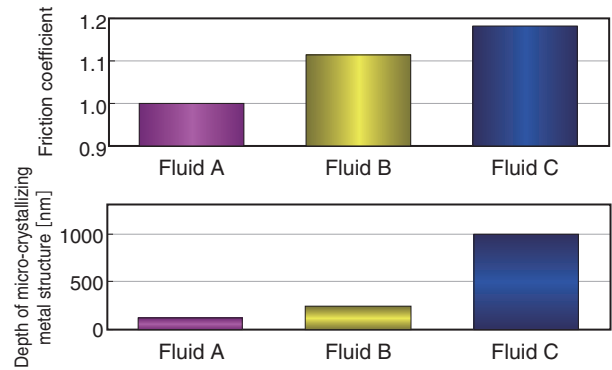


Fig. 10 Friction coefficient and depth of micro-crystallizing metal structure

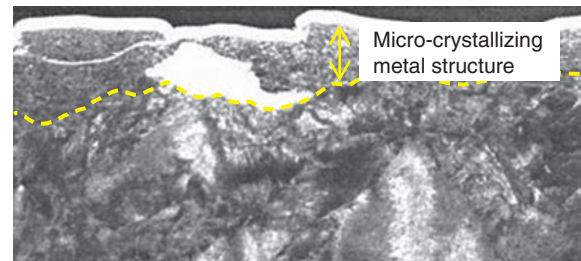


Fig. 11 Micro-crystallizing metal structure resulting from sliding friction

benchmark for evaluation was 18.1% higher than for the conventional CVT fluid in LOW ratio, and 10.8% higher in OD ratio (Fig. 12).

3.2.2. Attempting to reduce pulley V-surface wear

It was considered that because a correlation exists between the value of the coefficient of friction and the depth of the micro-crystallizing metal structure, the micro-crystallizing metal structure is formed in response to loads on the V-surfaces. Durability tests were conducted in LOW ratio, in which face pressure on the parts in contact is high, and in OD ratio, in which the face pressure is low in comparison to LOW ratio, and the state of the micro-crystallizing metal structures was compared using transmission electron microscopy (TEM). Martensite structures, characteristic of carburized heat treatments, were observed in the outer periphery of the drive pulley and the inner periphery of the driven pulley, which are used in the OD ratio, and in the outer periphery of the driven pulley, which is used in the LOW ratio, but the formation of a micro-crystallizing metal structure was not observed. However, in the inner periphery of the drive pulley, which is used in the LOW ratio, a micro-crystallizing metal structure of approximately $3\mu\text{m}$ in depth was formed, and cracking originating at the surface was observed close to the boundary between the martensite structure and the micro-crystallizing metal structure (Fig. 13). In addition, observation using scanning electron microscopy (SEM) showed that cracking also originated internally, at a depth of approximately $15\mu\text{m}$ from the surface (Fig. 14). Based on this evidence, it was considered that wear of the

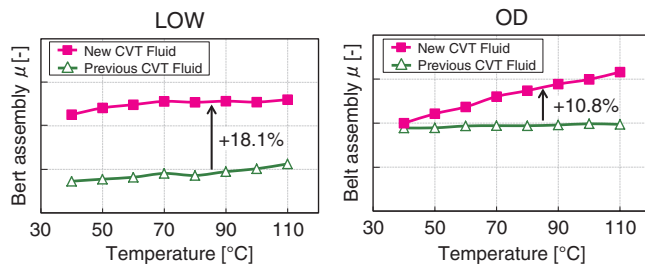


Fig. 12 Belt assembly friction coefficient

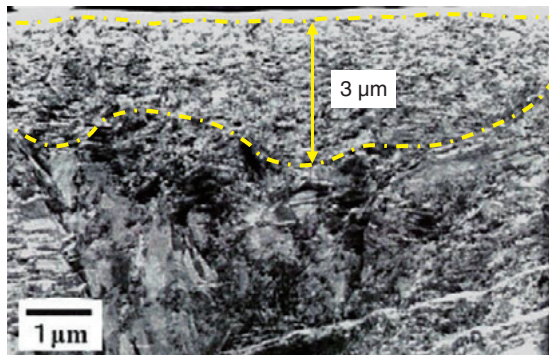


Fig. 13 Micro-crystallizing metal structure in drive pulley

V-surfaces occurs due to these cracks progressing, resulting in peeling of the surface. It was therefore necessary to attempt to prevent cracking originating at the surface and in the interior of the inner periphery of the drive pulley.

As methods of preventing wear, a zinc electric discharge coating was applied to the surface of the pulley in response to cracks originating on the surface, and carbonitride heat treatment was applied in response to cracks originating internally. A cross-section of the pulley close to the surface was observed using SEM following the durability test (Fig. 15). No cracks were observed either on the surface or in the interior of the cross-section.

3.3. Configuration to Help Control Movable Pulley Tilt

The trajectory of a metal pushing V-belt around the pulleys deviates slightly from the theoretical winding radius due to factors including the pulley tilt (Fig. 16). This is due

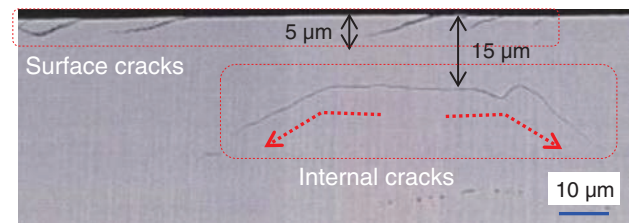


Fig. 14 Pulley cracks in durability test

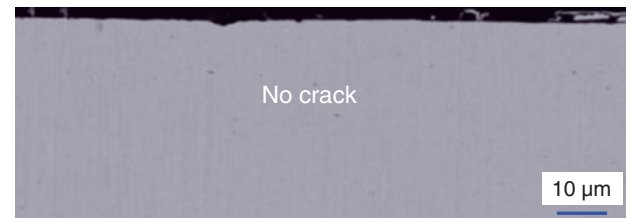


Fig. 15 Sectional view of pulley surface

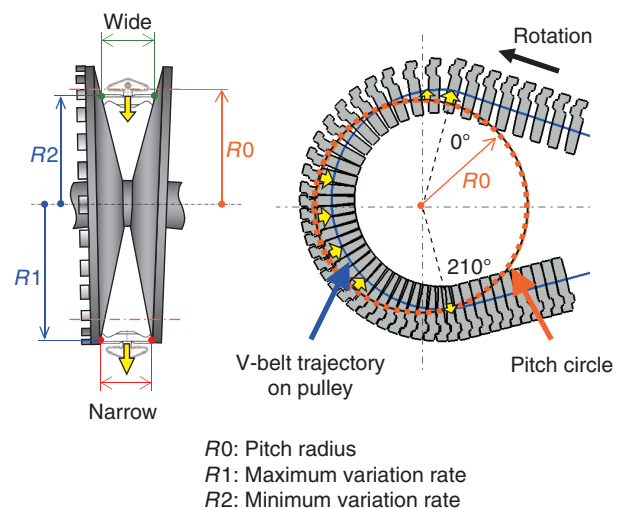


Fig. 16 Mimetic diagram of metal pushing V-belt trajectory on pulley

to the fact that when the movable pulley is pressed against the belt by thrust force, the distance between the V-surfaces of the section of the pulley that the belt is not wrapped around becomes smaller, while the distance between the V-surfaces becomes greater in the section that the belt is wound around, reducing the winding diameter in the latter section. This movement of the elements in the radial direction causes wear loss. Seeking to achieve its goal of increasing efficiency in the OD ratio during cruising, the research discussed here modified the configuration of the drive pulley pistons, which it was considered had a significant effect on the winding diameter and on pulley tilt, and succeeded in controlling pulley tilt and reducing deviation of the trajectory.

3.3.1. Pulley piston configuration

The generation of pulley thrust by the conventional configuration of the drive pulley is due to the No. 1 hydraulic chambers, located on the rear faces of the movable pulley V-surfaces, and the No. 2 hydraulic chambers, containing the secondary pistons that push the inner periphery of the pulley. Because the secondary pistons push on the inner periphery, approximately 50% of thrust acts on the inner periphery, and when the belt runs through the pulleys, the outer circumference of the movable pulley opens and the pulley becomes inclined. Because of this, the belt's winding trajectory deviates slightly from the theoretical winding radius. In order to help control this inclination, a No. 3 hydraulic chamber, which pushes the outer periphery of the movable pulley, was added to the outside of the No. 2 hydraulic chamber. Figure 17 shows a comparison of the previous and the new configurations. The transmission efficiency of the belt was studied by varying the thrust on the inner and outer peripheries of the movable pulley, and it was found that transmission efficiency was highest when pulley thrust was higher on the outer periphery side, and was at its highest when the ratio between pulley thrust on the inner and outer peripheries was 1:1 (Fig. 18).

3.3.2. Belt trajectory

The trajectory of the belt as it wraps around the pulleys was compared for the conventional and the

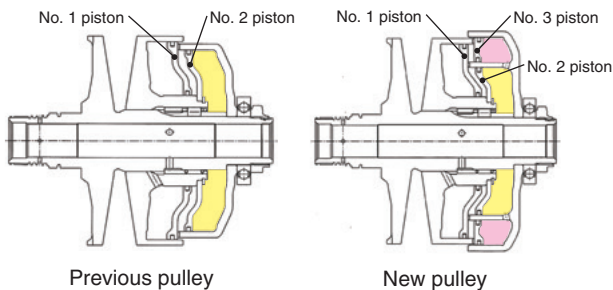


Fig. 17 Comparison of pulley configurations

new configurations in order to verify the effects of the modification of the configuration. The belt trajectory from the beginning to the end of winding around the pulleys was measured by eddy current displacement sensors positioned at 30° intervals (Fig. 19). 0° represented the beginning of the belt winding around the pulleys, and 210° represented the end. In terms of the trajectory of the section of the belt winding around the pulleys, the belt displays its highest radius at the commencement of winding around the pulleys, and the minimum winding radius occurs in the vicinity of the center of the section; the radius increases slightly at the end of winding around the pulley. Based on the difference between the trajectories of the belts in the conventional and the new configurations, it is considered that the friction loss due to movement in the radial direction displayed by metal pushing V-belts occurs because of the difference between the maximum radius at the commencement of winding around the pulley and the minimum radius at the central

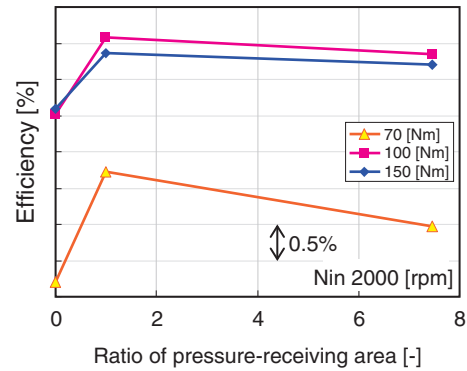


Fig. 18 Relationship between pressure-receiving area and efficiency

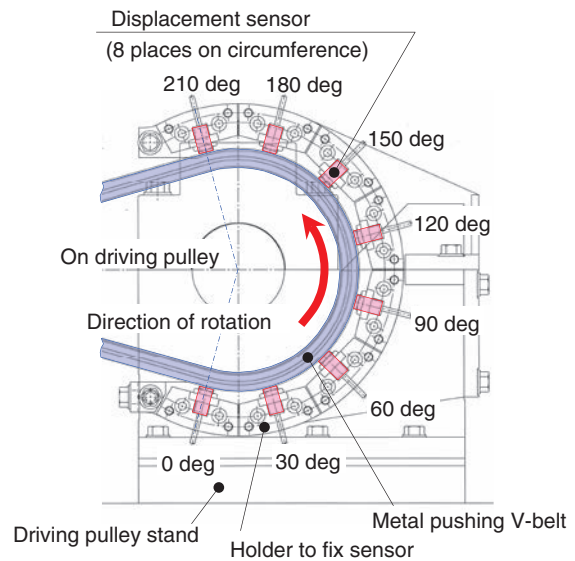


Fig. 19 Equipment for measurement of trajectory of metal pushing V-belt on pulley

part of the belt on the pulley (Fig. 20). The use of the new configuration has reduced the radius of the belt at the commencement of winding by 0.1mm against the conventional structure.

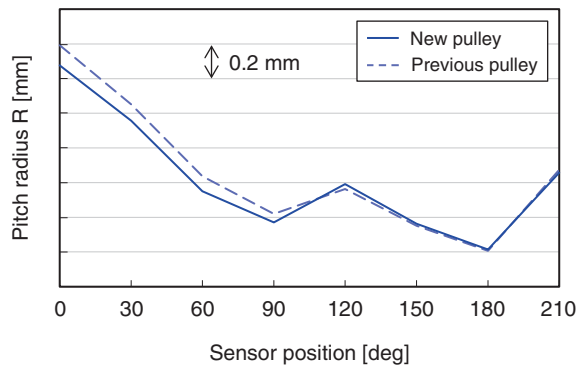


Fig. 20 Results of measurements of trajectory of metal pushing V-belt

4. Increase in Belt Transmission Efficiency

The effects of the three methods of increasing transmission efficiency studied in this project were verified in tests. The new control method employed reduced side pressure by approximately 40% and increased transmission efficiency by 2.6%. The use of the CVT fluid with an increased coefficient of friction increased the coefficient of friction by 10%, and setting side pressure in accord with the increased coefficient of friction increased transmission efficiency by 0.2%. The structure for control of tilt of the moving pulley reduced deviation of the belt-winding trajectory by 0.1mm, and increased transmission efficiency by 0.4%. The application of the three technologies to increase the transmission efficiency of metal pushing V-belts has increased the unit efficiency of the belt by 3.2% (Fig. 21).

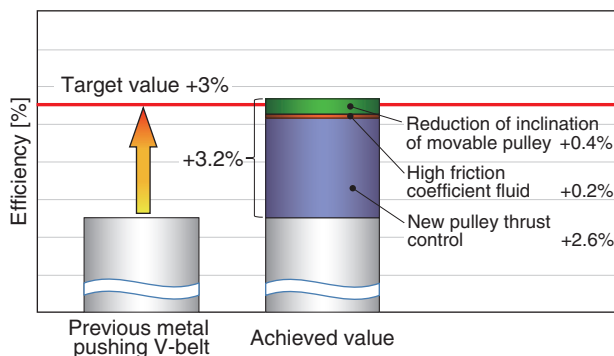


Fig. 21 Increase in efficiency

5. Conclusion

Three methods that were successful in increasing the unit efficiency of the belt have been developed.

- (1) Focusing on the correlation between the torque ratio, transmission efficiency, and the phase difference between the input and output shafts when engine speed fluctuates, the project developed a system making it possible to detect the torque ratio during vehicle operation and apply hydraulic control in order to operate the vehicle at the desired torque ratio. The optimization of pulley thrust increased transmission efficiency by 2.6% in OD ratio during cruising.
- (2) In order to increase the coefficient of friction between the pulleys and the belt, the mixture of additives to the CVT fluid was modified, increasing the coefficient of friction at the benchmark temperature for measurement of the coefficient of friction by 10%, and transmission efficiency by 0.2%. It was also discovered that carbonitride heat treatment and zinc electric discharge coating are effective in helping to prevent wear of the pulley V-surfaces.
- (3) In order to control deviation of the winding trajectory of the belt due to tilt of the movable pulley, a third piston was added to the outside of the second piston; the application of pulley thrust to the inner and outer peripheries of the movable pulley in a ratio of 1:1 reduced the amount of deviation of the winding trajectory of the belt by 0.1mm and increased transmission efficiency by 0.4%.
- (4) The simultaneous application of all three methods of increasing transmission efficiency resulted in a unit increase of 3.2% in transmission efficiency in a metal pushing V-belt in OD ratio during cruising.

6. Afterword

The development project discussed in this paper commenced with the question “Do the issues involved in increasing the transmission efficiency of CVT using metal pushing V-belts really only involve the belts themselves?” As discussed in this paper, the project determined that the belts were being used in an environment in which they could not adequately display their level of performance. The authors intend to push ahead with further performance increases in future, seeking to realize even higher figures.

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