

Optimization of V-surface Angle for Metal Pushing V-belt CVT

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ABSTRACT

The V-surface angles of the elements of metal-pushing V-belts were focused on, and an optimum angle was studied, in order to increase both torque transfer capacity and torque transfer efficiency in a CVT. The resulting reduction of the element V-surface angles from 11° to 9° produced an increase of approximately 20% in torque transfer capacity, and an increase of approximately 0.5% in unit efficiency in the OD ratio (close to a speed ratio of 0.45). With regard to the fatigue strength of the belt, measurements of the force between the shafts and durability tests showed that the ring tension is reduced and torque transfer capacity is increased in proportion to the degree of narrowing of the V-surface angles of the elements. The torque transfer efficiency of a metal-pushing V-belt is affected by the maximum level of variation in belt trajectory, as represented by the difference between the maximum and minimum values of the movement of the belt in the radial direction on the pulley. The research discussed in this paper indicated that control of the degree of variation in belt trajectory reduced friction loss due to the slip-motion of the belt in the radial direction, thus increasing torque transfer efficiency.

1. Introduction

The metal-pushing V-belt continuously variable transmission (CVT), invented in 1970 by Dr. Hub van Doorne, is today widely used in order to increase fuel efficiency and reduce exhaust emissions. Increases in torque transfer capacity and efficiency are constantly demanded from the metal-pushing V-belts that are framework components of the CVTs. However, it has been indicated that increasing transmission efficiency during high-speed cruising represents an issue in metal-pushing V-belt CVTs⁽¹⁾, and a variety of arguments has developed concerning the form of CVTs. A recent report has indicated that torque transfer efficiency can be increased if CVT pulley thrust is optimized⁽²⁾, and this suggests that there is still potential for increasing torque transfer efficiency. In addition, to date little research has focused on the relationship between the V-surface angles of the elements and torque transfer capacity and efficiency.

The research discussed in this paper focused on optimizing the element V-surface angles of a metal-

pushing V-belt CVT, and determined the optimum V-surface angle for increasing torque transfer capacity and efficiency. The results of the research have indicated that torque transfer capacity and efficiency can be increased against a standard metal-pushing V-belt if the V-surface angles are modified from the conventional 11° to 9° . This paper will present an overview of the research.

2. Development Goals and Targets

A variety of methods of increasing the torque transfer capacity and efficiency of a metal-pushing V-belt CVT can be considered: The metal-pushing V-belt itself can be modified, the pulleys and other components that clamp the belt can be modified, and the pulley control pressure can be optimized. The development discussed here set out to increase the torque transfer capacity of the metal-pushing V-belt by optimizing the V-surface angles of the elements, while achieving a level of torque transfer efficiency equivalent to or greater than that of a conventional belt. The torque transfer capacity of a metal-pushing V-belt

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CVT is defined as the limit time in which torque to be transmitted with conditions set for the number of input rotations, input torque, speed ratio, and the thrust of the pulley on the low-thrust side. The parameter used to evaluate torque transfer capacity in this research was the rate of increase in the durability time for which the unit was operated in the driving mode determined by the TOP ratio (the speed ratio for maximum vehicle speed).

The following development targets were set:

- (1) Metal-pushing V-belt torque transfer capacity: +20% against conventional belt; and
- (2) Metal-pushing V-belt torque transfer efficiency: Equivalent to conventional belt.

3. Development Concept

In order to increase the torque transfer capacity of a metal-pushing V-belt, it is necessary to reduce the stress generated on the belt. Table 1 shows a list of possible methods of reducing ring stress in order to increase torque transfer capacity by 20%. Increasing the width of the rings, increasing the number of laminated rings, and increasing the distance between the shafts of the CVT are available as methods of reducing ring stress, but they all result in an increase in the size and the weight of the belt.

The present development narrowed the standard V-surface angles of the elements to 9°. The development concept formulated was that by this means, torque transfer capacity could be increased by 20% with no increase in the size or weight of the CVT, and a torque transfer capacity equivalent to or greater than that of a standard belt could be achieved.

Table 1 Technique for reduction of ring stress

	Item changed in metal pushing V-belt			Item changed in transmission
Spec.	V-surface angle 11 → 9 [deg]	Width of rings 9.2 → 18.2 [mm]	Number of laminated rings 12 → 17 [Number]	Distance between shafts 156 → 170 [mm]
Weight	Same	Increase	Increase	Increase

4. Configuration of Metal-pushing V-belt and Names of Parts

The metal-pushing V-belts used in CVTs are made up of several hundred elements and two sets of layered rings (Fig. 1).

Figure 2 shows the configuration of a belt and the names of the individual parts.

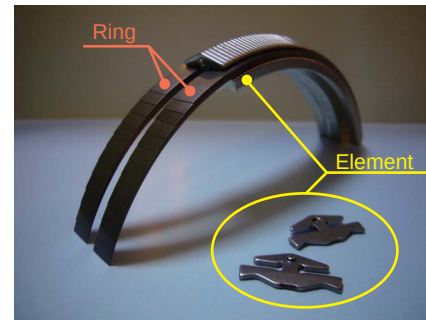


Fig. 1 Metal pushing V-belt

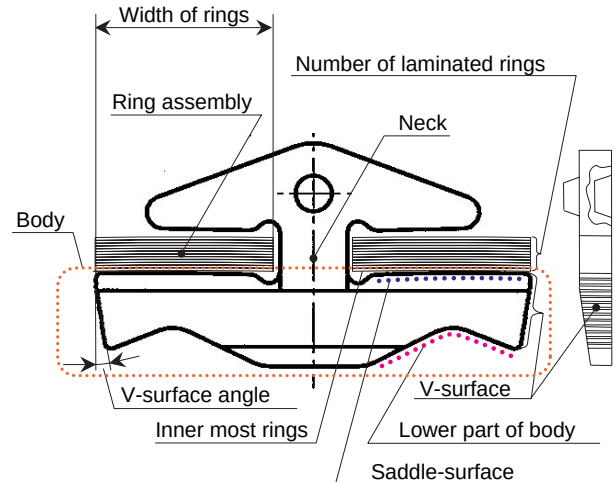


Fig. 2 Configuration of element and ring assembly

5. Specifications of Metal-pushing V-belt

When the V-surface angles of the elements of the metal-pushing V-belt were modified to 9° in this project, the form of the lower part of the element bodies was also modified, with consideration of the stiffness of the elements. Other specifications remained identical to those employed in elements with a V-surface angle of 11°.

5.1. Study of Element V-surface Stiffness

The V-surface stiffness is designed to maintain a constant theoretical V-surface angle irrespective of the speed ratio or the input torque. When the V-surface angle of the elements was modified, the vector of the thrust from the pulleys on the elements also changed (Fig. 3). Because of this, it was necessary to modify the form of the lower sections of the element bodies in accordance with the V-surface angle that was set (Fig. 4).

Figure 5 shows the method used to evaluate V-surface stiffness. In the figure, the uppermost section of the element V-surface is termed A, and the lowermost section is termed B. The form of the lower section of the element body was designed to help to ensure that the displacement of the V-surface given by A-B would be the minimum figure irrespective of the speed ratio.

5.2. Effect of Element V-surface Stiffness

The effect of the element V-surface stiffness on the maximum torque transfer capacity was studied. Figure 6 shows deformation diagrams for an element when the V-surface angle is constant and when it is not. In Fig. 6(a), the displacement of the V-surface is low, and the V-surface angle is constant, while in Fig. 6(b) the V-surface displacement is high, and the V-surface angle is not constant. Figure 7 shows the relationship between V-surface displacement (A-B) and maximum torque transfer capacity. The graph shows the percentage of the measured maximum torque transfer capacity when the V-surface angle is not held constant against the maximum torque transfer capacity when the angle is constant. When the V-surface angle is not held constant, the maximum transfer capacity is reduced by 3.2% against the case in which the

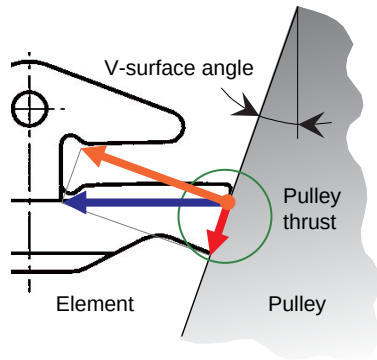


Fig. 3 Pulley thrust vector

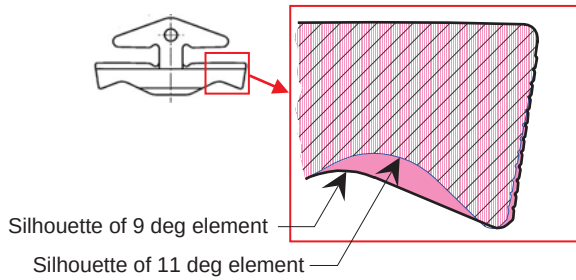


Fig. 4 Difference of outline of lower part of body

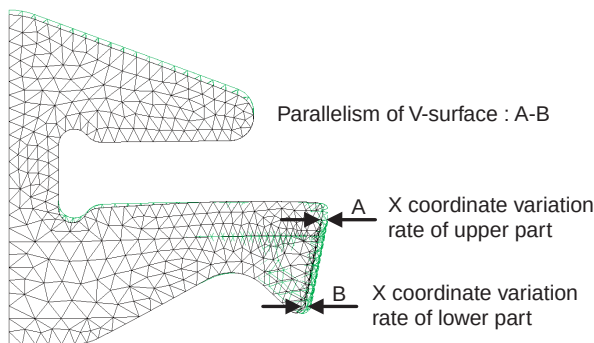


Fig. 5 Parallelism of V-surface

angle was constant.

A metal-pushing V-belt transfers torque through shearing of the boundary lubrication oil film formed between the element V-surfaces and the pulley V-surfaces. It is thought that in the case shown in Fig. 6(b), in which the V-surface displacement is high due to its stiffness, the element V-surfaces make localized contact with the pulley V-surfaces, and a boundary lubrication oil film cannot be formed effectively; because of this, the shear force declines⁽³⁾ and there is a reduction in the maximum transmitted torque. Therefore, the maintenance of the stiffness of the element V-surfaces is related to the maximum torque transfer that can be achieved.

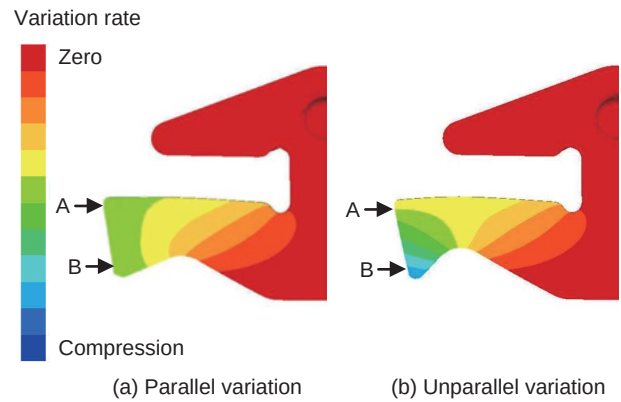


Fig. 6 Variation rate of element

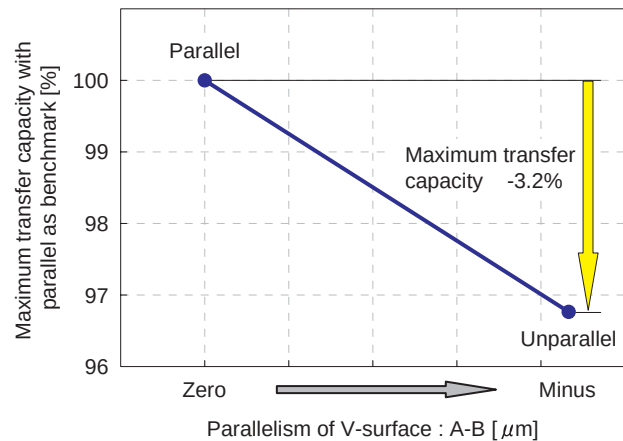


Fig. 7 Relation between rigidity of V-surface and maximum transfer capacity

6. Verification of Effect in Increasing Torque Transfer Capacity

The effect of the modification of the element V-surface angles to 9° in increasing torque transfer capacity was verified by checking the force between the shafts in simulations and actual measurements, and by conducting durability tests.

6.1. Estimation of Force between Shafts

Employing a simulation, it was estimated that the modification of the element V-surface angles from 11° to 9° would reduce the force between the shafts by approximately 10%, and that, as a result, the amplitude of stress on the rings, σ_a , would be reduced by approximately 4% and the mean stress on the rings, σ_m , would be reduced by approximately 7%, and that transfer capacity would increase.

Figure 8 shows results for the stress generated on the innermost rings of a metal-pushing V-belt for different phases of rotation at a speed ratio of 0.61. Figure 8(a) shows the positions of the rings and the phases of rotation used in the analysis.

Figure 8(b) shows results for a conventional metal-pushing V-belt using V-surface angles of 11° , while Fig. 8(c) shows results for a belt in which the V-surface angles had been set at 9° . Table 2 shows the stress amplitude (σ_a) and the mean stress (σ_m) determined from Figs. 8(b) and 8(c).

6.2. Measurement of Force between Shafts

The force between the shafts, produced by pulley thrust and torque transfer, acts between the pulleys and is proportional to the tension of the metal-pushing V-belt. The reduction of the element V-surface angles from 11° to 9° reduced the force between the shafts, and also reduced the contact pressure of the element saddle surfaces. It was therefore possible to compare the magnitude of ring tension by measuring the magnitude of the force between the shafts.

6.2.1. Measurement method

Figure 9 shows the method employed to measure the force between the shafts. A driven pulley stand was fixed to a base, and a drive pulley stand was fixed to a slide rail that could be freely moved in a direction orthogonal to the axis of rotation. One end of the drive pulley stand was connected to a fixed surface via a load cell. By this means, the load cell was able to measure the force generated between the shafts of the drive and driven pulleys by the tension of the metal-pushing V-belt.

6.2.2. Measurement results

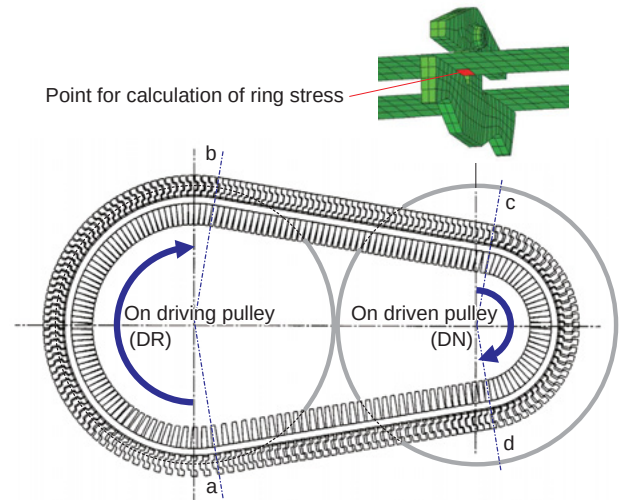
The results of the measurements showed that the reduction of the element V-surface angles to 9° reduced the force between the shafts by 16% in an operating mode corresponding to the top speed in an actual vehicle. This result displays the same tendency as the simulation results (Fig. 10).

6.3. Verification of Torque Transfer Capacity

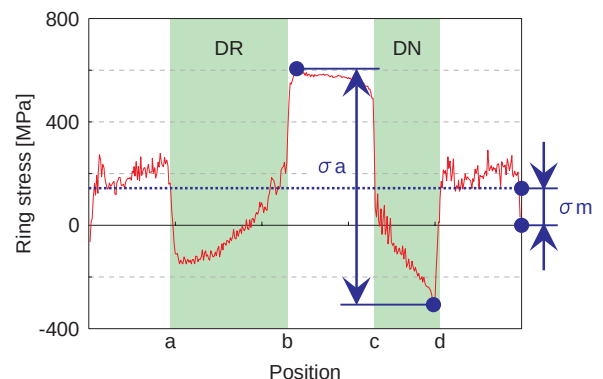
In order to verify the increase in torque transfer capacity in a metal-pushing V-belt in which the element V-surface angles had been reduced to 9° , the belt was subjected to a durability test extended beyond the limit

Table 2 List of calculated ring stresses

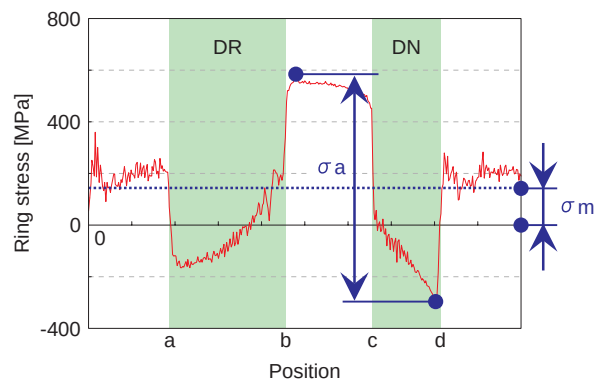
	V-surface angle		Rate of easing of stress
	11 deg	9 deg	
Stress amplitude σ_a	461 MPa	441 MPa	4%
Mean stress σ_m	144 MPa	134 MPa	7%



(a) Position on metal pushing V-belt in operation



(b) Ring stress diagram for 11 deg V-surface angle



(c) Ring stress diagram for 9 deg V-surface angle

Fig. 8 Calculated ring stress

time for a metal-pushing V-belt with V-surface angles of 11° . Figure 11 shows a comparison of the force between the shafts against the number of rotation cycles for belts with V-surface angles of 9° and 11° . The results show that the reduction in the force between the shafts when the V-surface angles are reduced to 9° produces a 23% increase in torque transfer capacity.

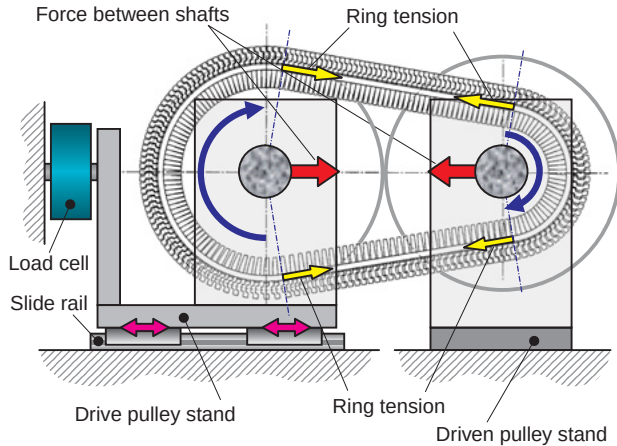


Fig. 9 Method for measurement of force between shafts

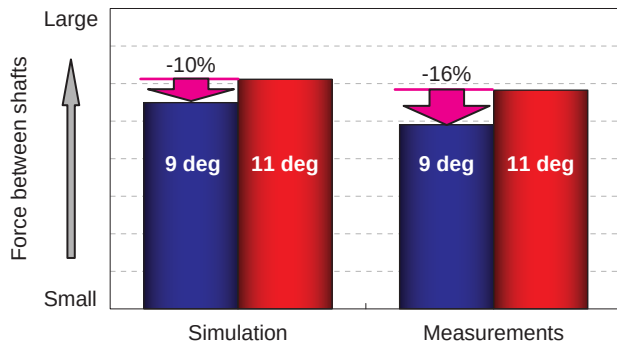


Fig. 10 Relation between V-surface angle and force between shafts

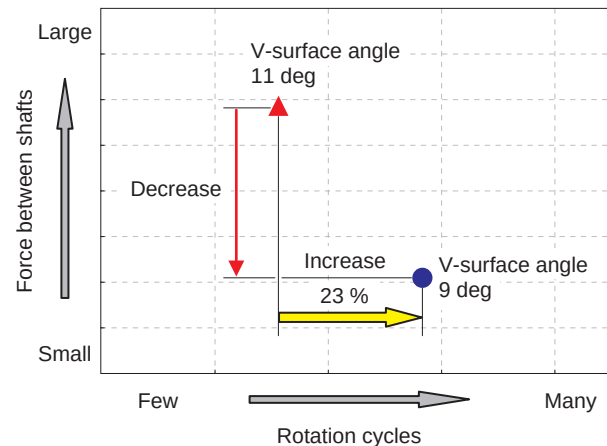


Fig. 11 Relation between rotation cycles of metal pushing V-belt and force between shafts

7. Verification of Torque Transfer Efficiency

During the verification of torque transfer efficiency, the degree of variation in the trajectory of the belt on the pulleys was measured and checked against measurements of efficiency, demonstrating the fact that the degree of variation in the belt trajectory affects efficiency.

7.1. Necessity for Measurement of Belt Trajectory on Pulleys

It was previously thought that due to the speed ratio, the trajectory of the belt on the pulleys would take on a pitch radius that represented the geometric radius. However, due to a variety of factors including the inclination of the pulleys under hydraulic pressure, the trajectory of the belt can diverge slightly from the winding radius. It is thought that these variations in belt trajectory result in a decline in torque transfer efficiency because the belt shifts in a direction orthogonal to the direction of rotation, in which torque is transferred. When the V-surface angles of the belt elements were modified, a different maintenance thrust force was necessary to maintain the speed ratio under the same operating conditions, and the belt trajectory therefore changed. It was therefore necessary to measure the trajectory of the metal-pushing V-belt around the pulleys for the different V-surface angles.

7.2. Method of Measurement of Variation in Trajectory

Measurement equipment was employed to measure the trajectories of the belts from the pulley entrance to the pulley exit. Figure 12 shows the equipment used to measure the trajectories of the belts on the drive pulley. Eddy current displacement sensors were positioned on the outer circumference of the belts, and the distance to the

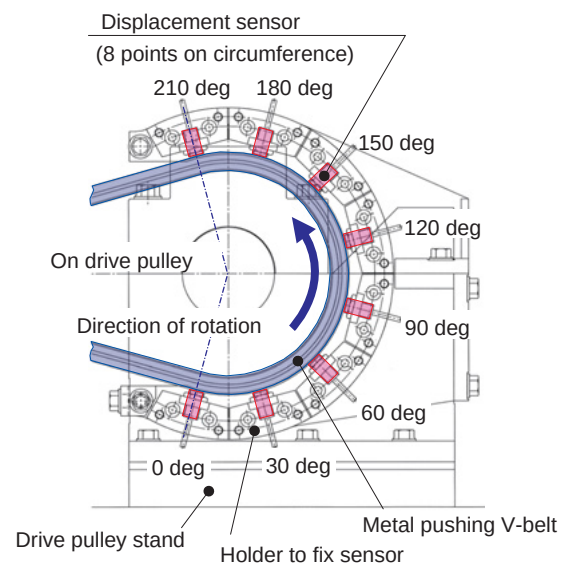


Fig. 12 Equipment for measurement of trajectory of metal pushing V-belt on pulley

outermost surfaces of the elements was measured. The measurement pitch was set at 30° , and eight sensors were used to cover a range of 210° from the entrance to the exit of the drive pulley. The winding radius (pitch radius) determined geometrically from the speed ratio was used as a benchmark, and the displacement data for each measured rotation phase was expressed as relative degrees of displacement from the pitch radius.

7.3. Maximum Variation of Belt Trajectory and Torque Transfer Efficiency

Figure 13 shows the results of measurements of variations in the trajectory of a metal-pushing V-belt. The maximum degree of variation in the trajectory of the belt is defined as the difference between the maximum radius and the minimum radius, with the pitch radius as the benchmark figure. Figure 14 shows a diagram of the state of the belt when wound around the pulley, based on the trajectory shown in Fig.13.

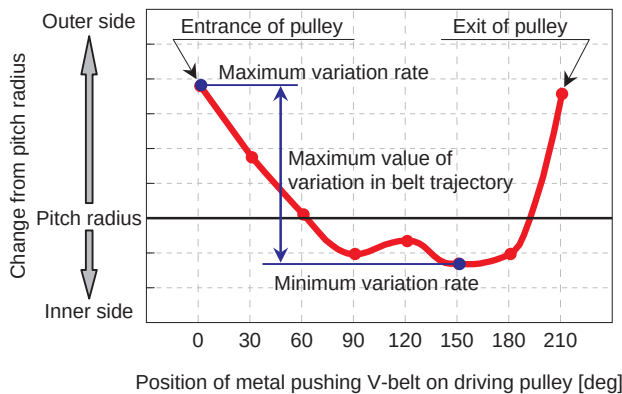


Fig. 13 Results of measurement of trajectory of metal pushing V-belt

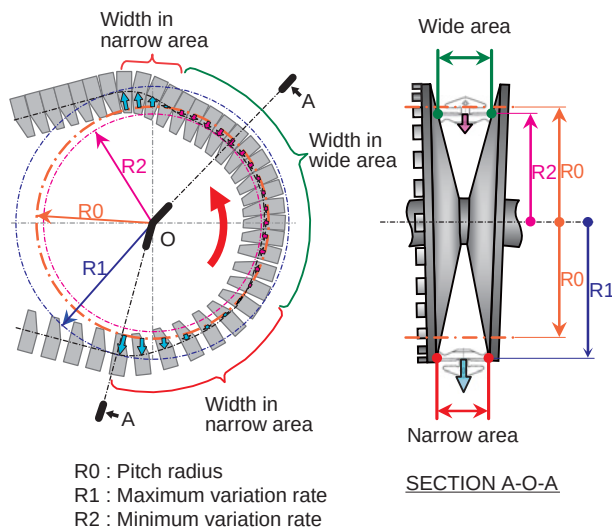


Fig. 14 Mimetic diagram of metal pushing V-belt trajectory on pulley

Because there are no elements present between the pulley V-surfaces in the area in which the belt is not wound around the pulley (the rotation phase between 210° and 360° from the pulley entrance), the gap between the pulley V-surfaces is narrow due to pulley deflection and other factors. Due to the effect of this phenomenon, the trajectory of the belt at the entrance of the pulley (the rotation phase between the entrance and 60°) and the exit of the pulley (the rotation phase between 190° and 210° from the entrance) is outside the pitch radius, and these are the highest radii among any of the measured points of the trajectory. In the area in which the belt is wound around the pulley (the rotation phase between the entrance and 210°), there are elements present between the pulley V-surfaces, and the gap between the V-surfaces is therefore wide. It is thought that because of this the belt trajectory approaches the inside of the pitch radius in the rotation phase between 60° and 190° from the pulley entrance.

It can be conjectured that these types of variation in the trajectory of the metal-pushing V-belt, producing a slip-motion in the radial direction, orthogonal to the direction of pulley rotation, act as a torque loss factor in torque transfer by the belt.

Next, the effect of variations in the belt trajectory on torque transfer efficiency was studied. The maximum value of trajectory variation was employed as the parameter for the variation in trajectory, and its relationship with torque transfer efficiency was examined (Fig. 15).

Using a metal-pushing V-belt with element V-surface angles of 9° , torque transfer efficiency was measured while varying the trajectory of the belt by varying the points of action of axial thrust force applied to the pulleys. A correlation was observed between the maximum variation in belt trajectory and torque transfer efficiency, with results displaying a tendency for efficiency to increase in proportion to the degree to which the variation in belt trajectory was controlled to a lower value.

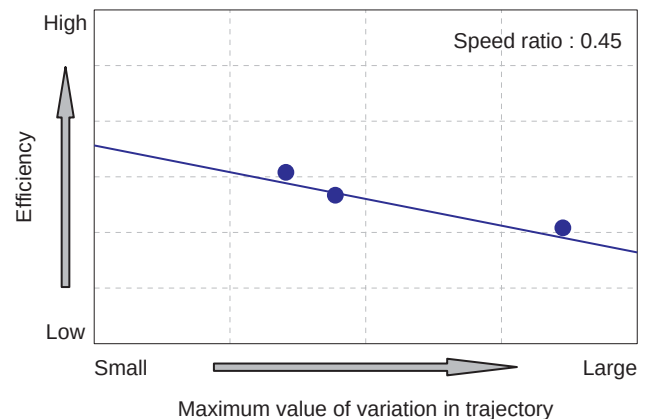


Fig. 15 Relation between maximum value of variation in belt trajectory and torque transfer efficiency

7.4. V-surface Angle and Maximum Variation in Trajectory

The relationship between the element V-surface angles and the maximum variation in belt trajectory was studied. Figure 16 shows a comparison of changes in the degree of variation in the belt trajectory against input torque for belts with element V-surface angles of 11°, 9°, and 7°, with 11° as the benchmark. The degree of variation in the trajectory of the belt was at its maximum in the belt with element V-surface angles of 7°, followed by the belt with element V-surface angles of 11°. The belt with element V-surface angles of 9° displayed the lowest level of variation in trajectory. This trend in the relationship between the V-surface angles of the elements and the maximum variation in belt trajectory remained unchanged when input torque was varied.

7.5. V-surface Angle and Torque Transfer Efficiency

Figure 17 shows the torque transfer efficiency for belts using elements with each of the V-surface angles as

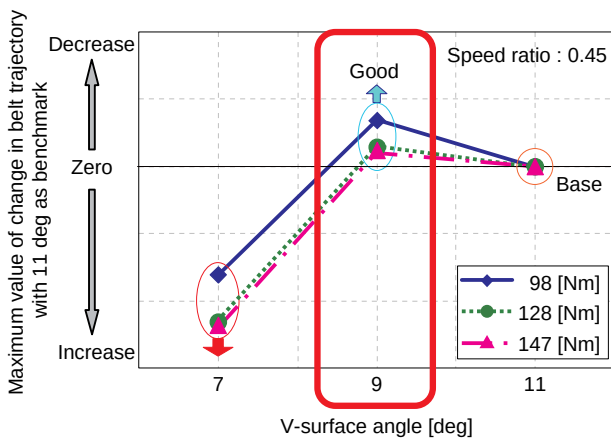


Fig. 16 Relation between V-surface angle and maximum value of change in belt trajectory

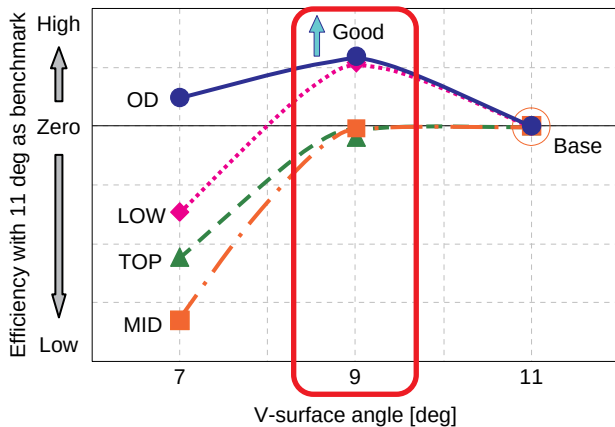


Fig. 17 Relation between V-surface angle and torque transfer efficiency

a difference with the torque transfer efficiency of a belt using elements with V-surface angles of 11° as the benchmark, for each speed ratio.

The belt using elements with V-surface angles of 9° displays identical torque transfer efficiency as the belt using elements with 11° V-surface angles at the MID and TOP ratios, and its efficiency reaches a maximum at the LOW and OD ratios. With the exception of the OD ratio, belts using elements with narrower V-surface angles than 9° displayed lower torque transfer efficiency than the belt using elements with 11° V-surface angles at all speed ratios. It can therefore be concluded that 9° is the optimum setting for the V-surface angle of the belt elements in order to realize maximum torque transfer efficiency at all speed ratios.

8. Vehicle Shift Characteristic

The shift characteristic of the conventional belt and the developed belt were compared in an actual vehicle.

8.1. V-surface Angle and Pulley Stroke

When the V-surface angles of the elements are made narrower, the pulley stroke is reduced in the same ratio range. Because of this, the stroke volume is also reduced, and the shift time during rapid acceleration and deceleration can therefore be reduced.

8.2. Results of Measurements of Shift Time

The belt with element V-surface angles of 9° displayed a faster hydraulic pressure rise time on the driven side than the belt with element V-surface angles of 11°, and its change in speed ratio towards the LOW side was faster to the same degree.

Figure 18 shows the shift characteristics in an actual vehicle under rapid deceleration (-4.9 m/s^2) from 60 km/h when the speed ratio returns to the LOW ratio side.

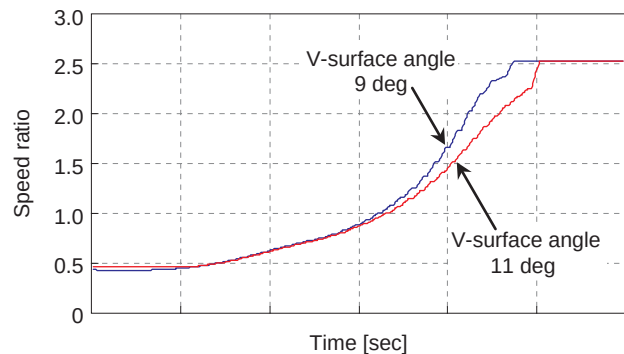


Fig. 18 Comparison of change in speed ratio with V-surface angle

9. Conclusion

The project discussed in this paper focused on the V-surface angles of the elements used in metal-pushing V-belts, and attempted to determine the optimum angle. The study showed that 9° was the optimum V-surface angle, and produced the following conclusions:

- (1) The use of element V-surface angles of 9° resulted in a 23% increase in torque transfer capacity against a belt using element V-surface angles of 11°;
- (2) A belt with element V-surface angles of 9° displayed equivalent or greater torque transfer efficiency to a conventional belt at all speed ratios, and displayed the highest torque transfer efficiency among belts with element V-surface angles of 7°, 9°, and 11°;
- (3) Narrowing the V-surface angles of the elements reduced the pulley stroke volume, enabling shift time during rapid acceleration and deceleration to be reduced; and
- (4) The maximum degree of variation in the trajectory of the belt when it is wound around the pulley affects torque transfer efficiency.

10. Afterword

Because natural selection goes into action if evolution stops, the development process is always a serious issue in the case of parts that are the focus of fierce competition for performance gains. Precisely because of this seriousness, it is necessary to clarify targets more precisely, and to pursue small details even in a specification that has until that point seemed to be perfected. The development discussed here has shown that if small changes are not overlooked, further potential for enhancement of performance becomes clear, and if this enhancement is pursued untiringly, the next stage of evolution can emerge.

In future developments, the authors wish to focus more closely on detailed points while engaging in further theoretical research on transmission mechanisms, in order to realize performance increases in CVTs.

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