

Enhancement of Power Transmission Efficiency in Metal Pushing V-belt CVT with Multi-V-surface Pulley and Modified-pitch Belt

Soichiro SUMIDA¹Tooru YAGASAKI¹Ryota AOKI¹Hikaru ASAI¹

ABSTRACT

To date, slips in the interior of the belt and pulley misalignment have been allowed as phenomena inherent to the mechanism of metal pushing V-belt CVTs. The research discussed in this paper reduced loss, which had conventionally been allowed, for the first time ever in order to further increase efficiency. A slip in the interior of the belt is generated by a differential between the belt pitch radius and the ring winding radius when the belt is wrapped around the pulleys. Slippage between the elements and the rings was reduced by reducing this radius differential. In addition, changing the shape of the pulley V-surface from 11 deg to 9 deg and adopting a curved multi-V-surface shape made it possible to reduce the tensile force of the rings and thus reduce the contact load in the sliding sections. Furthermore, the developed pulley-belt mechanism reduces the stroke differential between the drive and driven pulleys when shifting and controls the occurrence of misalignment irrespective of the speed ratio. This has increased power transmission efficiency by a maximum of 2.4% and by 0.9% averaged over the speed ratio width.

1. Introduction

There has recently been a rapid shift towards the electrification of automotive powertrains against the background of the need to reduce consumption of fossil fuels. Nevertheless, it is predicted that even in 2030, there will still be 30% or more of conventional vehicles that use internal combustion engines alone as their power source⁽¹⁾. Given this, it is necessary to boost fuel efficiency above current levels in conventional vehicles also. Considering these market trends, the application of metal pushing V-belt CVTs is increasing as a means of boosting fuel efficiency performance. Honda has conducted in-house development of metal pushing V-belts⁽²⁾, and manufactures the units in-house. Figure 1 shows a breakdown of loss in a metal pushing V-belt CVT in JC08 mode. From this, it can be seen that the metal pushing V-belt is the element generating the greatest amount of loss. This results from the fact that the geometric trajectory of the metal pushing V-belt differs from its actual trajectory. Up to date research focusing on metal pushing V-belt loss in order to reduce this loss has studied the optimum V-surface angle⁽³⁾ and configurations that will reduce pulley thrust and control

pulley inclination⁽⁴⁾. However, the slipping that occurs in the interior of the belt and the twisting of the belt itself (termed “misalignment” below) have been accepted as phenomena inherent to the metal pushing V-belt CVT mechanism.

The research discussed in this paper focused on reducing the loss originating in the mechanism of the metal pushing V-belt CVT, and sought to create a theoretical element form and advance production technologies in order to

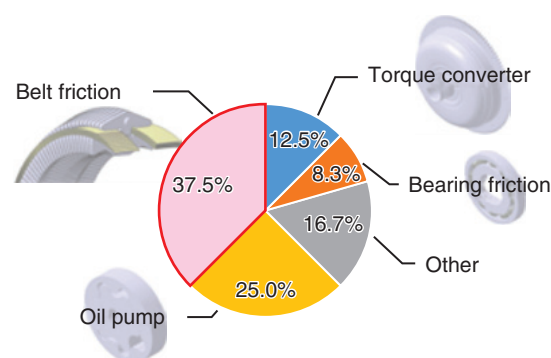


Fig. 1 Breakdown of power consumed in CVT (during operation in JC08 mode)

¹ Automobile Center

realize that form. The research was successful in boosting the performance of metal pushing V-belt CVTs. This paper presents an overview of the theory involved in the research.

2. Development Aims

In a CVT, the belt runs between a fixed and a movable pulley. Power is transmitted from the drive pulley to the driven pulley by the friction force of the belt V-surfaces (Fig. 2). The metal pushing V-belt is composed of two sets of layered rings and several hundred elements (Fig. 3). The belt transmits power by means of the mutual pushing of the elements. The pitch radius of the metal pushing V-belt is determined with the positions at which the elements mutually push each other as the rocking position (Fig. 4). As Fig. 5 shows, because there is a difference in the belt pitch radius, R , and the ring winding radius, $R + \alpha$, a circumferential velocity differential, ΔV , is generated between the elements and the rings. This circumferential velocity differential causes the elements and rings to slip

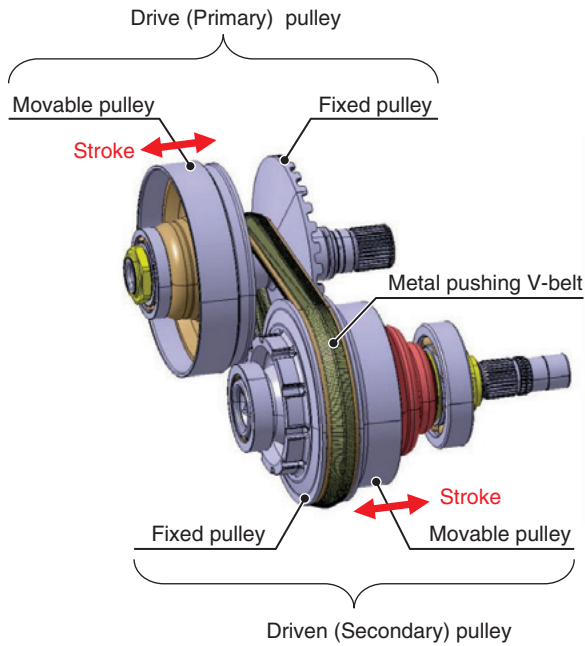


Fig. 2 Configuration of pulleys and metal pushing V-belt

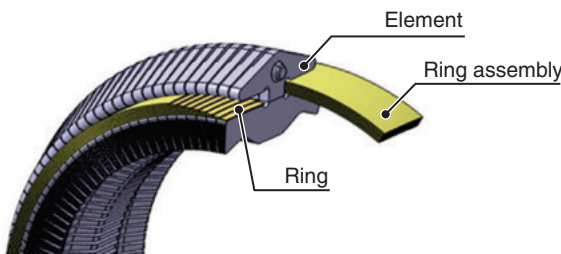


Fig. 3 Configuration of metal pushing V-belt

with the rotation of the pulleys. Similarly, the ring thickness produces a difference in the winding radius between each layered ring, and as a result, the circumferential velocity differential generates slip between the rings.

The friction loss in each section of the metal pushing V-belt resulting from slip in the interior of the belt, P , is given by Eq. (1), using the coefficient of friction of the slipping sections, μ_s , the vertical load on the slipping sections, N , and the slip velocity, ΔV .

$$P = \mu_s N \Delta V \quad (1)$$

In other words, the friction loss due to slip in the interior of a metal pushing V-belt could be reduced by reducing the slippage per unit time between the elements and the rings and between the rings themselves (termed “slippage” below) and the ring force pressing on the elements. The research discussed here ought to increase power transmission efficiency with a focus on this point.

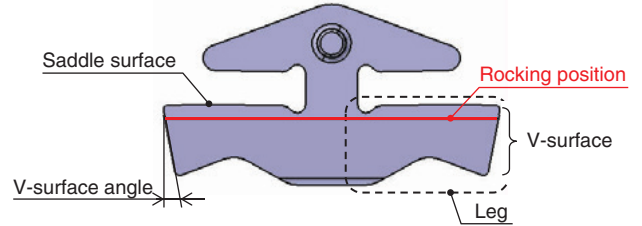


Fig. 4 Configuration of belt element

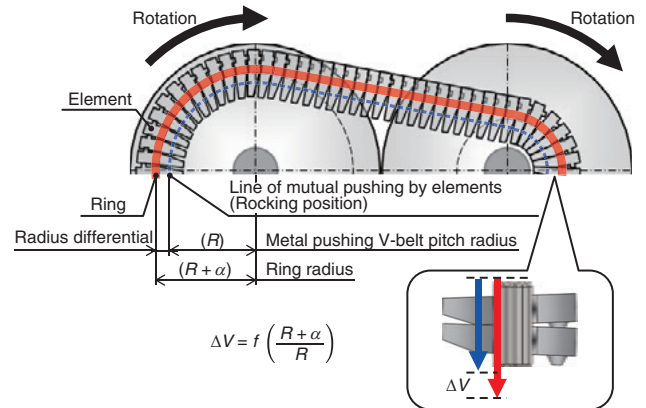


Fig. 5 Velocity differential between elements and rings

3. Method of Increasing Power Transmission Efficiency

The specifications of the pulleys and the belt were changed, as shown in Table 1, in order to increase power transmission efficiency. Broadly speaking, three items were changed. The first of these was the moving of the element rocking position closer to the saddle surface (Fig. 4)

Table 1 Specifications of pulley and belt

Item		Current model	Developed model
Pulley	Distance between pulley axes	156 mm	156 mm
	V-surface	Single angle 11 deg	Multiple angle 9 deg / Round
Belt	Element width	24 mm	24 mm
	Rocking position	1.00 mm	0.55 mm
	V-surface	Single angle	Multiple angle
		11 deg	9 deg
		Grooved	Grooved
	#1 ring diameter	208.8 mm	208.8 mm

in order to reduce the differential of the winding radius between the elements and the ring of the metal pushing V-belt, α , thus reducing slippage, ΔV . In addition, in order to respond to the issue of element durability following the reduction of the winding radius differential, contact surfaces with contiguous elements were set on the backs of each element. The second point changed was the reduction of the pulley V-surface reference angle, in order to lower the tensile force of the metal pushing V-belt and reduce the contact load, N , between the elements and the rings and between the rings themselves. The third change was making the outer circumference of the pulley V-surface curved (Fig. 6), in order to reduce the pulley belt clamping force (termed “pulley thrust” below), which increases with the reduction of the pulley V-surface angle and additionally increases ring durability by reducing belt misalignment. Curvature was also added to the element V-surfaces with the change in the shape of the pulley V-surfaces.

3.1. Change in Element Rocking Position

Since the metal V-belt is a pushing belt, the elements receive power from the pulleys, and the speed of the belt is determined by the position at which the elements mutually push each other (the rocking position). By contrast, the

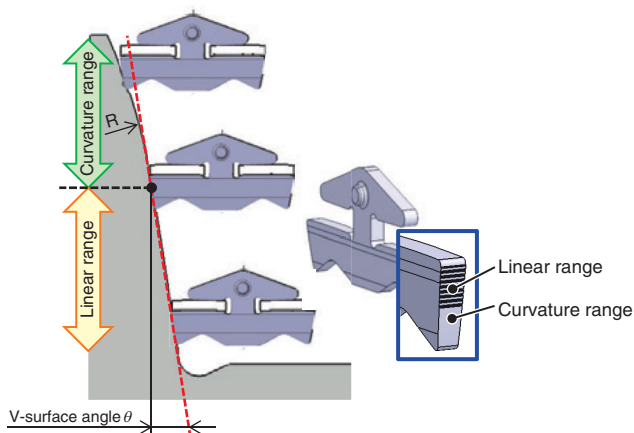


Fig. 6 Pattern diagram of pulley and belt

rings move by being dragged as they rest on the element saddle surfaces. Due to this, the elements and the rings rotate without slipping on the pulley side, on which the winding length of the metal pushing V-belt is greater⁽⁵⁾. Slipping of the elements and rings occurs in the other pulley, where the belt winding length is smaller due to the difference in the winding radius. Similarly, the rings mutually slip because they are layered in the direction of the pulley winding radius. In other words, it would be possible to reduce slippage by attempting to equalize the winding radius of the elements and rings, which are generating slip, to the greatest extent possible.

The slippage occurring between the elements and the rings and between the rings themselves could be changed by using a speed ratio that would change the winding radius differential between the drive pulley and the driven pulley. Slip would not occur using Mid ratio, in which a differential between the winding radius of the metal pushing V-belt around each pulley was not generated, and friction loss would also be minimized using this ratio. On the other hand, slip would become conspicuous at Low or High ratios, in which the winding radius differential would be large, and friction loss would also become high.

In the research under discussion, the rocking position was reduced from 1.00 mm to 0.55 mm in order to reduce the winding radius differential between the elements and the rings (Fig. 7).

Since the slippage between the elements and the rings increases in proportion to the winding radius differential between the elements and the rings, α , a reduction of 0.45 mm in the winding radius differential would result in a 45% reduction in slippage (Fig. 8). However, in the case of the layered rings, slippage would not change because their configuration would not be changed.

Despite the fact that the utility of the measure has long been known⁽⁶⁾, the rocking position has not been moved closer to the shear-machined section (the element profile). This is due to concerns that the creation of gaps between the elements would hinder the maintenance of a state of stable contact between the elements, affecting their durability. Two causes can be considered for this. The first of these is that the leg section (Fig. 4) becomes

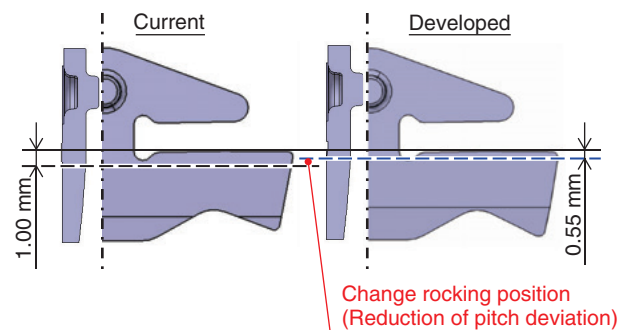


Fig. 7 Comparison of current and developed elements

thinner as a result of changes in the thickness of the plate (droop) when the element is formed. Figure 9 shows a contour diagram that expresses element plate thickness as height data. This diagram shows that the rocking section is lower than the upper section of the saddle surface in the element with a thin leg section. The second cause is the occurrence of mutual displacement between elements. Due to the configuration of the metal pushing V-belt, there is no constraint on parts other than the rings and pulleys, and micro-displacements occur between the elements when the belt is in operation⁽⁷⁾. As the rocking position is 1.00 mm in a conventional element, this displacement can be ignored. However, the displacement cannot be ignored in an element with a lower rocking position. Since the metal pushing V-belt receives power from the pulleys, a load is applied to the V-surface (the edge of the leg). If gaps occur between the elements at this time, excessive bending stress is generated on the elements in comparison to a state in which there are no gaps. As a result, it was important to respond to this issue for the application of the technology discussed here. In order to do so, step differences were engineered on the back surfaces of the elements as shown in Fig. 10, creating a shape that made it possible to maintain the state of contact⁽⁷⁾. Figure 11 shows the state of contact between the elements with and without the step difference. The step difference allows the elements to receive power across their entire width, while also making it possible to maintain durability.

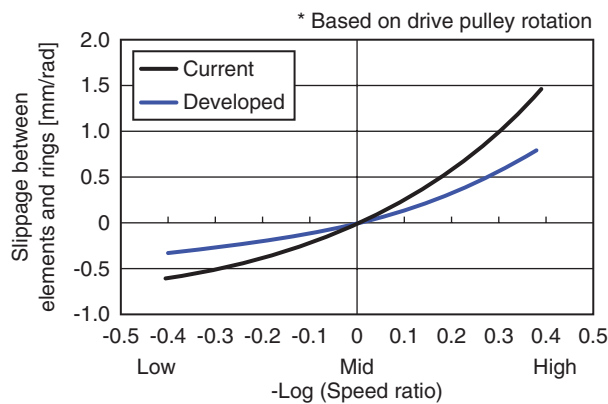


Fig. 8 Reduction of slippage between elements and rings

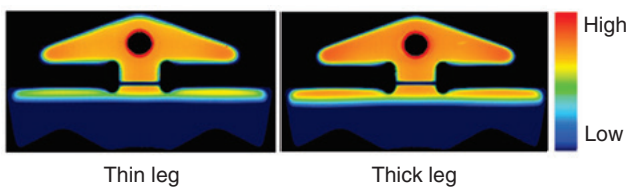


Fig. 9 Element thickness indicated by height

3.2. Application of Multi-V-surface Pulley

When the position of the metal pushing V-belt wound around the pulleys (the speed ratio) has been determined, the force that pushes the elements in the pulley radial direction due to pulley thrust and the force that maintains the elements of the metal pushing V-belt in that position due to the rings are in equilibrium. In other words, the contact load between the elements' saddle surfaces and the rings, N , is determined. As Fig. 12 shows, the contact load N corresponds to the radial component of pulley thrust, Q , and the pulley V-surface angle, θ . The contact load is therefore dependent on pulley thrust and the pulley V-surface angle, and friction loss between the elements and rings could be reduced by reducing their radial components. However, pulley thrust Q plays a role in determining torque

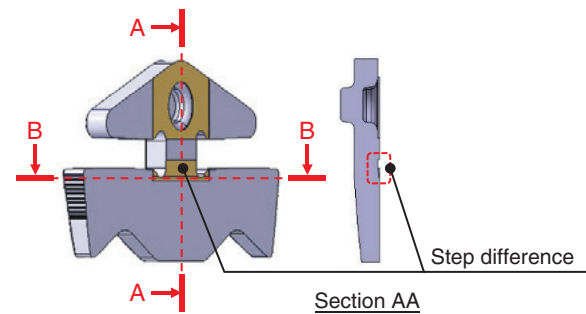


Fig. 10 Step difference on back of element

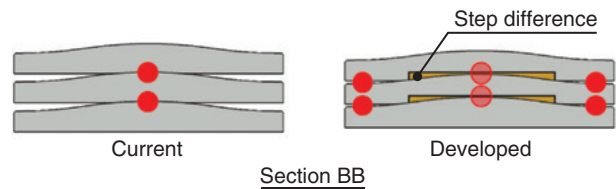


Fig. 11 Contact position of element

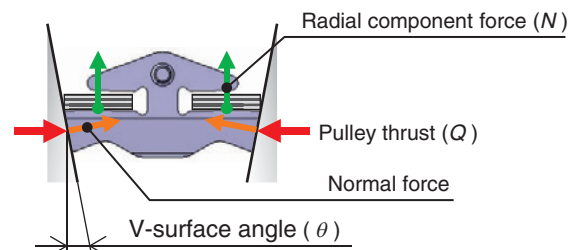
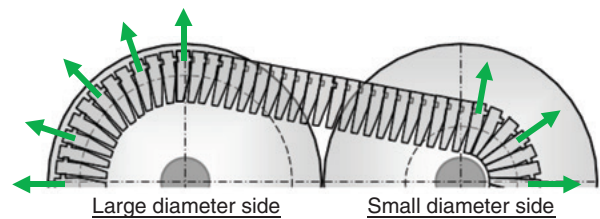


Fig. 12 Force applied to pulley and belt

transmission capacity. The torque transmission capacity of each pulley, T , can be expressed as Eq. (2) using the winding radius, R , and the belt friction coefficient, μ_b , allowing the necessary pulley thrust for torque transfer to be determined.

$$T = \frac{2\mu_b R Q}{\cos \theta} \quad (2)$$

It should be noted that the effect of operating conditions and other factors is omitted here, allowing for unambiguous expression. In addition, the pulley thrust has a low-thrust side that determines the torque transmission capacity given by Eq. (2) and a high-thrust side that determines the speed ratio. Depending on the speed ratio, these can be either the drive pulley or the driven pulley. At this time, because the necessary thrust is added to the winding radius component of the V-surface angle θ at the high-thrust pulley that determines the speed ratio, thrust in excess of the torque transmission capacity is applied. In other words, the system presents antagonistic characteristics: in the case of torque transmission capacity, the smaller the V-surface angle θ , the more pulley thrust can be reduced, while in the case of the high-thrust side that determines the speed ratio, the higher the V-surface angle θ , the more the added thrust can be reduced.

The research under discussion changed the pulley V-surface shape from an 11 deg single shape to a 9 deg curved and multi-V-surface shape in order to reduce the contact load between the element saddle surfaces and the rings. As a result, the pulley V-surface angle θ , which determines the contact load N , was set to transition from a narrow angle to a broad angle in the pulley radial direction (Fig. 13).

This made it possible to reduce the contact angle when the winding radius of the metal pushing V-belt is small, and thus to reduce the contact load between the element saddle surfaces and the rings. In addition, because it was also possible to increase the contact angle when the winding radius is large, it was possible to reduce the pulley thrust on

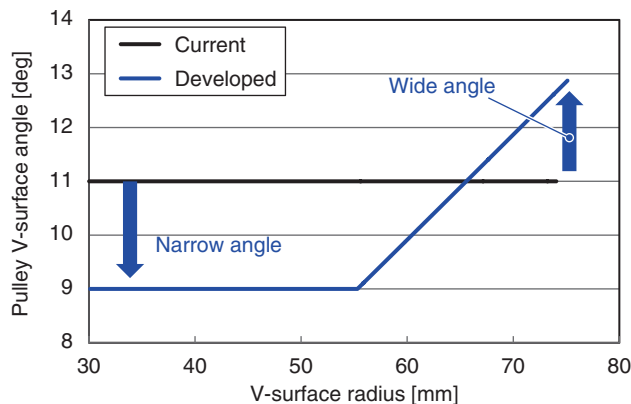


Fig. 13 Radius and angle of pulley V-surface

the high-thrust side, which increases as the angle narrows. Figure 14 shows the effect of reduction in the contact load between the element saddle surfaces and the rings through the use of the multi-V-surface shape as the force acting between the pulley axes (termed “pulley inter-axial force” below). The pulley inter-axial force is the force received by the pulley axes when the metal pushing V-belt is pushed by pulley thrust.

3.3. Reduction of Misalignment

Three points were taken into consideration in the adoption of the multi-V-surface pulley. The first of these was not increasing the stroke of the movable pulley against the previous type (11 deg single V-surface shape). The second was to attempt to help prevent the pulleys and the belt V-surfaces from making point contact on the side with the small metal belt pitch radius. The third point was to attempt to remove the stroke differential with the movable pulley, thus making it possible to do away with misalignment. Metal pushing V-belt CVTs change the pitch radius of the metal belt via the stroke of the movable pulleys on the drive and driven sides, and determine the arbitrary speed ratio by means of the radius differential. The necessary stroke at this time determines the size of the transmission, and the movable pulley stroke when creating each speed ratio is determined by the distance between the pulleys and the circumference of the metal belt. As Fig. 15 shows, there is a difference in each pulley stroke necessary for shift between the drive and driven sides, and half of this difference becomes misalignment.

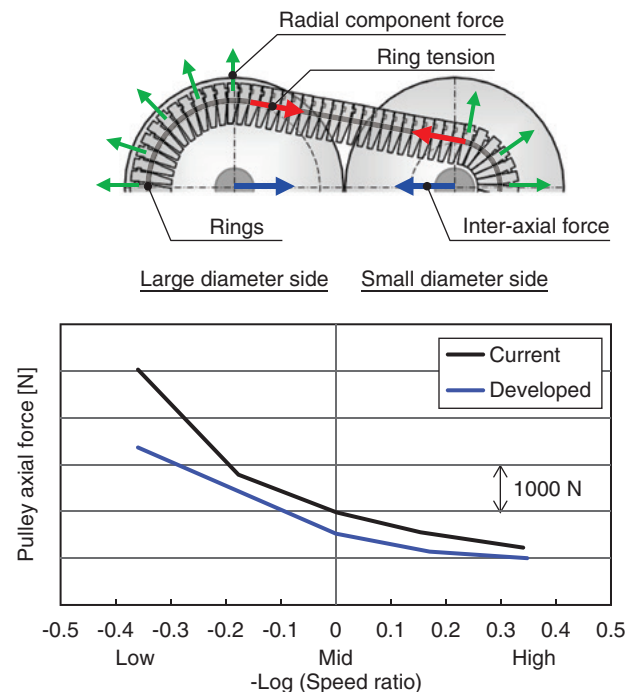


Fig. 14 Pulley inter-axial force

Misalignment, C_{MA} , is given by Eq. (3), using the winding radius, D , and the distance between the drive and driven pulleys, s , when the speed ratio, i , equals 1.0 (Mid ratio).

$$C_{MA} = \frac{D^2(i-1)^2}{\pi s(i+1)^2} \tan \theta \quad (3)$$

In the research under discussion, the generating line function for correction of misalignment via the pulley V-surface shape was defined using Eq. (4), with Y as the pulley shaft axis, and X as the radius axis.

When $X \leq$ Mid ratio radius,
Pulley shape coordinates = $X \tan \theta$ (4-1)

When $X >$ Mid ratio radius,
Pulley shape coordinates = $X \tan \theta + C_{MA}$ (4-2)

As it is necessary to add the actual misalignment correction amount to the extent of the curvature engineered into the elements, Eq. (4) is expressed in a simplified form.

By imparting the amount corresponding to misalignment to the pulley generating line in this way, the pulley stroke is rendered almost exactly the same for each pulley (Fig. 16). The ability to control misalignment irrespective of the speed ratio contributes to boosting the alignment of the elements.

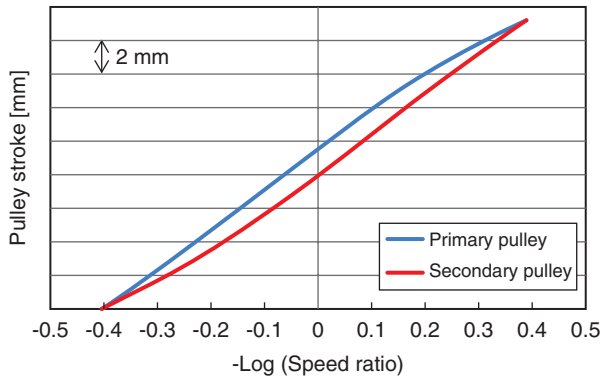


Fig. 15 Pulley stroke in 11 deg pulley

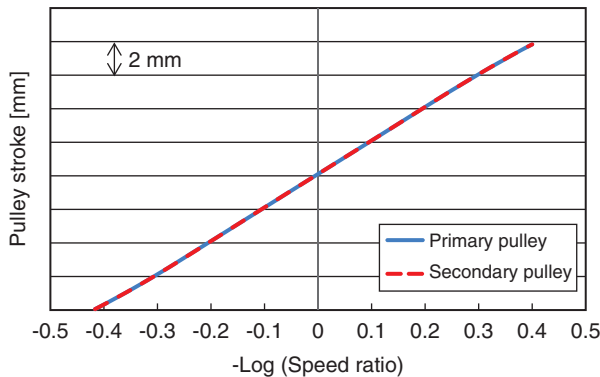


Fig. 16 Pulley stroke in developed pulley

4. Effect in Increasing Power Transmission Efficiency

Power transmission efficiency was tested in unit tests at different speed ratios for each of the two methods of boosting power transmission efficiency under study. Power transmission efficiency varies as a result of factors including the difference in the winding radius at the drive and driven pulleys due to the speed ratio. Due to this, power transmission efficiency was evaluated at five speed ratios: Low, Mid, High, and the ratios 1.5 and Top, which are intermediate between these. The results showed an increase of 2.4% in Low ratio, 1.6% in High ratio, and 0.9% in average power transmission efficiency (Fig. 17). Here, the rate of increase in average power transmission efficiency is expressed as the average of the rate of increase for each speed ratio that was set. It is considered that the power transmission efficiency declined in the Mid ratio because the V-surface angles of the drive and driven pulleys were the same, and the pulley thrust on the high-thrust side increased due to the effect of reducing the angle.

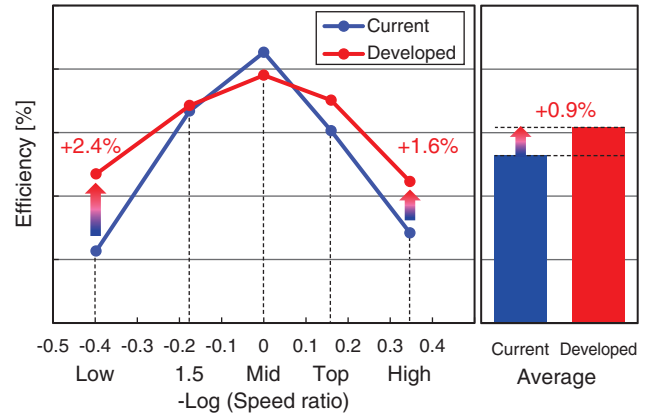


Fig. 17 Power transmission efficiency

5. Conclusion

Friction loss due to slip in the interior of a metal pushing V-belt was reduced in order to increase the power transmission efficiency of CVTs.

- (1) The pulley winding radius differential between the elements and the rings of the metal pushing V-belt was set low by changing the rocking position of the elements, making it possible to reduce friction loss by reducing slippage. In addition, the issue of durability was responded to by stabilizing the mutual contact between the elements.
- (2) The pulley V-surface shape was changed to a multi-V-surface shape using the characteristics of the high-thrust and low-thrust sides, making it possible to reduce the

contact load between the elements and the rings of the metal pushing V-belt, thus reducing friction loss.

- (3) The application of a multi-V-surface shape made it possible to correct misalignment due to the stroke differential between the drive and driven pulleys, boosting the alignment of the metal pushing V-belt.

The application of these changes to the pulley-belt mechanism increased average power transmission efficiency by 0.9%.

References

- (1) Jidosha shin jidai senryaku kaigi chukan seiri (an) hosoku shiryo, Ministry of Economy, Trade and Industry, P. 18, (2018) (in Japanese)
- (2) Yagasaki, T., Aoyama, H., Saito, T., Ishii, K., Okada, Y., Arikawa, M.: Development of Metal Pushing V-Belt for Continuously Variable Transmission, Honda R&D Technical Review, Vol. 14, No. 1, p. 181-190
- (3) Yagasaki, T., Aoyama, H., Ichijo, S., Totsuka, H., Harada, M.: Optimization of V-surface Angle for Metal Pushing V-belt CVT, Honda R&D Technical Review, Vol. 22, No. 1, p. 169-176
- (4) Ichijyo, S., Yagasaki, T., Ando, T., Sakagami, K., Sumida, S.: Study of High-efficiency CVT Shifting Mechanism using Metal Pushing V-belt, Honda R&D Technical Review, Vol. 26, No. 1, p. 34-41
- (5) Saito, T., Miyamoto, K.: Transmission Efficiency Prediction for CVT Metal V-belt with Ratio Feedback Control, CVT-HYBRID 2010 Proceedings, p. 29-34
- (6) Morimoto, Y.: Mudanhensokuki CVT nyumon, Grand Prix BOOK PUBLISHING CO.LTD., p. 53-56, (2004)
- (7) JP, Patent Application No. 6094911, (2017)

■ Author ■



Soichiro SUMIDA



Tooru YAGASAKI



Ryota AOKI



Hikaru ASAI