Study on power transmitting efficiency of CVT using a dry hybrid V-belt.

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Abstract

This paper presents the net power transmitting efficiency of CVT using a newly developed dry hybrid V-belt. The efficiency was measured by using a devised testing machine, which eliminates other power losses due to peripherals such as shaft flanges. Torques on both pulleys were measured with high accuracy by using strain gauges which were glued on the cantilever shafts.

The CVT efficiency is divided into three regions with respect to applied torque. At a low range of applied torque: region I, the efficiency of CVT increases sharply with respect to the applied torque, because the bending loss is almost constant for applied torque but the torque increases the total transmitting power. At region II (a middle range of applied torque), the efficiency is also constant with respect to transmitting torque since the relative energy loss due to belt bending decreases while the energy loss due to elastic slip increases with increasing the transmitting torque. They are equivalent with each other at this region. The efficiency sharply decreases at region III due to the remarkably increasing of the slip. The transmitting efficiency increases with the low contraction force. The CVT shows the high transmitting efficiency at the speed ratio 1.0.

The transmitting efficiency decreases when the CVT system has the misalignment, because the sharing deformation of the belt strand influences the transmitting efficiency as well as the bending deformation. The appropriate initial setting misalignment exists to reduce the influence of the misalignment.

It is found that the relationship between the traction coefficient and the transmitting efficiency is independent on the contraction force, speed ratio and the misalignment. The traction coefficient could be a non-dimensional applied torque for characterizing the efficiency of the dry hybrid V-belt type CVT.
1. Introduction

The Continuously Variable Transmissions (CVT) using dry hybrid V-belts have higher power transmitting efficiency than metal pushed V-belt type CVT due to high frictional coefficient between a V-belt and pulleys. Because lubrication oil and devices for lubrication are not necessary to operate "the dry CVT".

On studying the dry CVT efficiency, we have three topics in our research. At first: some papers reported that this dry CVT has over 95% efficiency [1], but in their study, the efficiency of them were totally measured in a unit. There were several power losses such as bearing, torque-meter loss and others in such a system. Therefore we measured the efficiency excluding such losses with high accuracy. Secondly: it can be also said that deference of the speed ratio causes to change the transmitting efficiency. The applicable indicator for the transmitting efficiency should be proposed independent on the speed ratio for easy evaluation of the CVT system. At last: current type CVT has a structural misalignment [2] to change the speed ratio in wide range by moving the one side of the pulley flange. It is important to investigate the influence of the misalignment on the transmitting efficiency of the dry CVT. However, few reports have been published describing the efficiency of the dry hybrid V-belt CVT considering the above three topics.

This paper describes the characteristics of the transmitting efficiency, and proposes the applicable indicator to show the variation of the efficiency of dry hybrid V-belt CVT with high accuracy. The mechanism that explains the change of the transmitting efficiency is also discussed when the CVT has the misalignment.

2 Experimental apparatus

2-1 Structure of dry hybrid V-belt

Figure 1 shows the schematically illustration of a CVT belt used in this study. The structure of the belt is hybrid, made of blocks and tension members. A couple of tension members are inserted into grooves between two multiple arms of 204 pieces of lateral H-shaped blocks. Blocks consist of aluminum alloy covered with a heat resisting resin. Rubber tension members are reinforced by aramid fiber. Blocks sustain the pulley thrust with high stiffness and produce the frictional force for applicable power transmission. Tension members should be flexible for which the belt fits with pitch radii in spite of high tensile strength to the elevated tension. The belt has 26 degree wedge angle, 25mm pitch width and 612mm belt length.
2.2 CVT test machine and test conditions.

Figure 2 shows a schematic view of the CVT running test machine and torque measuring system in this study. This test machine consists of the dry hybrid V-belt, driver and driven pulleys. The groove widths of the pulleys were fixed to constant. The machine has AC motor that provides constant input revolution speed, and weights for applied torque and contraction force. The contraction force $F_s$ was measured by a load cell and revolution speed at each shaft $N_{in}$ and $N_{out}$ are measured by proximity sensors. Eight sheets of strain gages were glued on cantilever shafts attached slip-rings to measure net torque on the pulleys with high accuracy as shown in figure 2(b). The measured torques $T_{rin}$ and $T_{rout}$ does not included other torque occurring at bearings or torque-meters by this system. In this study, speed ratio $i$, contraction force $F_s$, applied torque $T_{rout}$, misalignment distance $C$ were changed.

![Block Tension member](image1)

(a) Dry hybrid V-belt assembly and (b) consists of a block and tension member.

![Proximity sensor](image2)

(a) Experimental apparatus and (b) newly measuring method.
3. Results and discussion

3.1 Three region of the transmitting efficiency

The transmitting efficiency $\eta$ was calculated by equation (1), and the slip ratio was calculated by equation (2), where $N_{out}$ is the revolution speed of driven pulley at no applied torque. Figure 3 shows the transmitting efficiency $\eta$ and the slip ratio $s$ with respect to the applied torque $T_{out}$.

$$\eta = \frac{T_{out}N_{out}}{T_{in}N_{in}} \times 100$$  \hspace{1cm} (1)

$$s = \frac{N_{out} - N_{out0}}{N_{out0}} \times 100$$  \hspace{1cm} (2)

The variation of $\eta$ with respect to the $T_{out}$ can be divided into three regions. Region I existed at the $T_{out}$ under 30Nm where the $\eta$ increasing sharply. In the middle range of the $T_{out}$ ($T_{out}$=30~60), there was region II where transmitting efficiency was almost constant about maximum efficiency. Region III where the transmitting efficiency decreasing suddenly was observed at the $T_{out}$ over 60Nm. The slip ratio increased linearly in the region I and II, and then it increase sharply in the region III.

The variations of $\eta$ with respect to the $T_{out}$ can be explained by considering the power losses occurring between belt and pulleys. The driving loss are mainly caused by following two. One is bending loss due to the deformation of tension members to bend on the pulley, which is given by equation (3). The other is the slipping loss due to elastic deformation of the belt to transmit the power given by equation (4).

$$\Delta P_b = \frac{EI\pi}{30R} N$$  \hspace{1cm} (3)

$$\Delta P_s = \frac{v}{2EAR^2} T_{out}^2$$  \hspace{1cm} (4)

![Graph showing the variations of transmitting efficiency and slip ratio with respect to applied torque](image-url)

Figure 3: Variations of (a) transmitting efficiency and (b) slip ratio with respect to applied torque. Speed ratio 1.0, contraction force 2.0kN.
Where, $E$ is Young's modulus, $I$ is the moment of inertia of area, $A$ is the cross section of the tension member along the belt and $v$ is the belt velocity. In this study, the $\Delta P_t$ can be considered almost constant for any conditions if speed ratio is constant. But $\Delta P_t$ depends on the applied torque. Figure 4 shows calculation results by the equations (3) and (4) describing the relationship between the $Tr_{out}$ and the $\eta$. The calculated result well agree with the experimental result in the regions I and II.

In a low range of the applied torque: the region I, the efficiency of the CVT increases sharply with respect to the applied torque, because the bending loss is almost constant for the applied torque but the torque increases the total transmitting power. In region II, the efficiency is also constant with respect to the transmitting torque since the relative energy loss due to belt bending decreases while the energy loss due to elastic slip increases with increasing the transmitting torque. They are equivalent with each other at this region. The efficiency sharply decreases in the region III due to the remarkably increasing of the slip.

![Figure 4: Comparison between calculation results and experimental result. speed ratio 1.0, contraction force 2.0kN.](image)

### 3.2 Influence of the running condition on the transmitting efficiency

#### 3.2.1 contraction force

Figure 5(a) shows the transmitting efficiency $\eta$ and the slip ratio $s$ with respect to the applied torque $Tr_{out}$ when the contraction force $Fs$ changed. Figure 5(b) shows the transmitting efficiency at $Tr_{out}$=20N for any conditions of the $Fs$. The $\eta$ decreased with increasing $Fs$ because frictional force increased due to the belt penetration to the pulley radius direction.

The traction coefficient $\lambda$ is calculated by equation (5), and it has been generally used to evaluate the transmitting ability regardless belt types. Where $T_t$ is the tight side tension, $T_s$ is the slack side tension and $\theta$ is the angle of strand.

$$\lambda = \frac{T_t - T_s}{T_t + T_s} = \frac{Tr_{out} \cos \alpha}{R_{DN} F_s}$$

The slip ratio was generally expressed for the function of the traction coefficient as the applicable indicator of the transmitting capacity. Gerbert analyzed pulley thrusts considering the belt motion in pulleys of a rubber V-belt.
type CVT and expressed the contraction force and the pulley thrust as the function of the traction coefficient $\lambda$ [3]. Figure 6 shows the transmitting efficiency $\eta$ and the slip ratio $s$ evaluated by using the traction coefficient $\lambda$. The $\lambda$ can divide the $\eta$ into three as well as the $Tr_{out}$. Furthermore there is the region I in $\lambda = 0.0 - 0.3$, the region II in $\lambda = 0.3 - 0.6$ and the region III in $\lambda = 0.6$ at any $Fs$. It can be seen that the variations of the $\eta$ and the $s$ almost independent on the $Fs$ in the regions I and II. If the $Fs$ increases, the transmitting power increases at the same traction coefficient $\lambda$, because the $\lambda$ is the non-dimensional applied torque. However, the bending loss is constant at any traction coefficient. Therefore the transmitting efficiency $\eta$ increases when the contraction force $Fs$ increases at any $\lambda$ in the regions I and II.

![Figure 5: Variations of transmitting efficiency with respect to applied torque.](a) Transferring efficiencies at applied torque 20Nm.](b)

![Figure 6: Variations of (a) transmitting efficiency and (b) slip ratio with respect to traction coefficient. Speed ratio 1.0.](a)

### 3.2.2 speed ratio

Figure 7 shows the $\eta$ and the $s$ with respect to the $\lambda$ when the speed ratio $i$ changed. It can be seen that the variations of the $\eta$ and the $s$ with respect to the $\lambda$ almost independent the $i$ as well as the contraction force $Fs$ changed. The
transmitting efficiency at \( i = 1.0 \) has the highest of the three other ratios in all regions. Figure 8 shows the calculated bending losses with respect to the \( \lambda \) when the speed ratio \( i \) changes. This means that the \( \eta \) shows maximum at \( i = 1.0 \).

![Figure 7: Effect of speed ratio on (a) transmitting efficiency and (b) slip ratio. Contraction force 2.0kN.](image)

![Figure 8: Difference of bending loss. Contraction force 2.0kN.](image)

### 3.3 Influence of the misalignment

Figure 9 shows the \( \eta \) and the \( s \) with respect to the \( \lambda \) when the misalignment distance \( C \) changed. The misalignment is the offset of each pulley to axial direction due to changing the speed ratio. The variations of the transmitting efficiency with respect to the traction coefficient were divided into three regions even if the misalignment distance \( C \) was changed.

As shown in this figure when the \( C \) increased, the \( \eta \) decreased in the regions I and II; however, less difference was observed in the region III. It can be supposed that the slip ratio is not affected by the misalignment. The misalignment of the CVT should make the shearing deformation at strands as shown in figure 10. Shearing deformation causes constant quantitative loss as the bending loss, much affects of the \( C \) on the \( \eta \) was observed in the region I. Figure
11 shows the influence of the misalignment on the $\eta$ when the speed ratio changes. The $\eta$ at $i=1$ shows the highest because that has the longest strand i.e. the shearing deformation is the smallest at $i=1$.

Figure 12 shows the absolute value of the shearing deformation with respect to the speed ratio when the initial setting misalignment $C_{ini}$ changed. $C_{ini}$ is the misalignment distance at the speed ratio $i=1$. The relationship between the speed ratio and the misalignment was calculated by equation (6) [3].

$$ C = \left[ (R_{DN} - R_{DNO}) - (R_{DRO} - R_{DR}) \right] \tan \frac{\alpha}{2} $$

Where, $R_o$ is the pitch radius at the misalignment distance $C = 0$ and $\alpha$ is the wedge angle of the V-belt. Maximum of the shearing deformation shows the smallest at $C_{ini}=0.384$, i.e. there is the applicable initial misalignment to reduce the influence of the misalignment on the transmitting efficiency.

Figure 9: Effect of misalignment distance on (a) transmitting efficiency and (b) slip ratio. Contraction force 2.0kN, speed ratio 1.0.

Figure 10: Sharing deformation of belt strand due to misalignment distance.
Figure 11: (a) Effect of misalignment distance on transmitting efficiency. 
(b) Variation of sharing deformation with respect to speed ratio.

Figure 12: Effect of initial setting misalignment distance on absolute value of sharing deformation.

4. Conclusions

1. Variations of the transmitting efficiency can be divided into three regions, and it changes increasing, constant and decreasing in each region. The bending loss influences the transmitting efficiency in the region I, and bending loss and slipping loss influence the efficiency in the region II. The slipping loss influences in the region III.

2. Regardless of the contraction forces, the speed ratios and the misalignments, the traction coefficient can characterize the variations of the transmitting efficiency. In the region II, at the $\lambda=0.3-0.6$, the transmitting efficiency shows high and constant.

3. The transmitting efficiency decreases when the CVT has the misalignment especially in the region I. The influence of the misalignment on the transmitting efficiency is the least at speed ratio $i=1$ where sharing deformation is the smallest.

4. There is the applicable initial setting misalignment distance to reduce the influence of the misalignment on the transmitting efficiency.
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References

