Slip behavior in the variator by measuring the belt speed

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Slip behavior in the variator
by measuring the belt speed

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Report number: DCT 2006.33

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Eindhoven, March 2006
Preface

This report is part of the internship at the section Power Trains of the master track Automotive Engineering Science (AES) of the faculty Mechanical Engineering. The report is a continuation of the report “Development of a belt speed sensor for the CVT-CK2” written by Aart-Jan van Eck.

The report describes experiments with the pushbelt speed measurement system.

Thanks go especially to my coach Bram Bonsen. Furthermore is greatly indebted to Toon van Gils, Erwin Meinders and Wietse Loor, who helped me by activating the pushbelt speed measurement system.
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Summary

The efficiency of a Continuously Variable Transmission (CVT) can be optimized by decreasing the variator clamping forces. A lower clamping force level leads to a decrease in power consumption of the CVT hydraulic pump and that results in decreasing fuel consumption.

If the clamping force level will be decreased, the risk of belt slip increases. In order to prevent slip in the variator the slip of the belt must be detected exactly.

Last year a belt speed sensor for the CVT-CK2 was developed and realized. Only the connection between the sensor framework and the transmission-house still had to be developed. This is done by a self carried subframe which is mounted in side-cover of the transmission-house. These mechanical parts have proven themselves during the measurements. In brief, all the displacements of the belt can be followed during up and down shifting.

The belt speed sensor generates an electric block-signal. By counting the blocks during a certain time the pushbelt speed can be calculated. After conditioning and filtering the measured speed gives a good measure. The expected belt speed and the slip behavior in the variator can be made estimated.

The unloaded measurements show that the pushbelt always will slip at the primary pulley if the ratio goes from UnderDrive to OverDrive. But if the ratio goes from OverDrive back to UnderDrive the belt starts slipping at the secondary.

The loaded measurements were only done at one of the extremity positions of the moveable pulley sheaves, namely UnderDrive. These measurements establish that if the torque transmission is increasing the system reaches its maximum traction coefficient and the belt starts to slip. Here slip occurs between the primary pulley and the pushbelt.

One disadvantage of the pushbelt speed measurement system is the used inductive sensor. The pole tip of this sensor wears down. This results in a loss of signal after a period of use. For this problem a solution should be found.
Chapter 1

Introduction

A Continuously Variable Transmission (CVT) differs from a manual transmission. It does not have a gearbox with a set number of gears, like manual transmission and other automatic transmissions. The CVT is a stepless power transmission with an infinite variability of the ratio between the highest and lowest gears. One of the most common type is the Van Doorne pushbelt CVT.

The main part of the pushbelt CVT system is the variator. The variator consists of two wedge shaped pulleys and a metal V-belt. Every pulley has a moveable and fixed sheave. Because of the axial moveable pulley sheaves, the V-belt runs on variable diameters and is stepless shifting between the extreme UnderDrive (UD or LOW) and OverDrive (OD) ratio, see figure 1.

The working principle of the CVT is that the torque or power is transmitted from the primary to the secondary pulley by friction. To prevent slip between the pulley sheaves and the belt at all times, high clamping force levels are needed. The level of the clamping force is based on the maximum torque of the engine and on the maximum shockloads from the road. The disadvantage of the high clamping force levels are losses in the CVT by the hydraulic pump. It has also negative effect on the pulleys and the belt, because it increases deformation. This results in wear, fatigue and increasing of the internal friction in the belt.

Nowadays the fuel consumption of a car with a CVT is comparable to a car with a manual transmission. But the efficiency of the CVT can be optimized by:

- increasing the ratio coverage;
- reducing actuation losses;
- decreasing variator clamping forces.

Figure 1.1 The extreme variator ratios.
Lowering the variator clamping forces can lead to a decrease of 5% in fuel consumption, because of the decrease in power consumed by the CVT hydraulic pump. Another additional advantage is the decrease of stresses in the pushbelt.

If the clamping force levels are decreased, the risk of belt slip increases. In order to prevent slip in the variator the slip of the belt must be estimated, so that the clamping forces can be adapted to every situation, for instance in case of torque peaks.

At the moment it is possible to calculate the theoretical slip in the variator according the data of the measured angular speed of both pulleys and the working radius. Last year the University of Eindhoven has developed and realized a belt speed sensor for the CVT-CK2.

The goal of this internship is to do research to the behavior of slip in the variator of the CVT-CK2. Chapter 2 will describe the montage of the belt speed sensor. Next, in chapter 3, the unloaded measurements will be discussed. Chapter 4 will be engaged in modeling about place-detection of the slip. After this in chapter 5 the loaded measurements will be discussed. Finally some conclusions and recommendations will be done as a result of the measurements.
Chapter 2

Pushbelt speed measurement system

The pushbelt speed measurement system for the CVT-CK2 is developed and realized by Aart-Jan van Eck. The foundations of the layout are explained in his report. The belt speed measurement system consists of three mean components namely a framework, an inductive sensor and a connection between the sensor system and the transmission-house. The sensor framework fits around the belt and follows all the displacements of the pushbelt. On this framework the inductive sensor is mounted, which generates an electrical signal if a segment passes. All these components have been made and are available. Only the connection between the sensor system and the transmission-house needs some attention during mounting the pushbelt speed measurement system in the CVT-CK2.

2.1 Assembly

For mounting the sensor framework to the transmission-house, two blocks were made. These blocks ought to be fixed by four bolts on the transmission-house. Unfortunately it is not easy. In practice it is not possible to make the holes from inside, because it is not visible with a drill. And the hole cannot be made from the outside of the transmission-house, because then the exact position cannot be located. So another connection had to be developed. The working plan of the new connection can be found in appendix A. The new connection is a framework with fixing points at one side, a so-called self carried subframe. The sensor framework will be mounted in the self carried subframe, see figure 2.1.

![Figure 2.1](image)

**Figure 2.1** Left the sensor framework with blocks and right the new self carried subframe.
The subframe is developed in such a way that the framework can follow the maximum displacements of the belt in the direction of the moveable sheaves during up and down shifting. The sloped sides avoids that the pushbelt hits the subframe. In this case the subframe is not mounted in the transmission-house, but in the side-cover which supports the primary and secondary pulley.

A disadvantage of the complete pushbelt speed measurement system in the CVT-CK2 is the extensive assembly method. First the pulleys have to be mounted in the side-cover, before the belt can be removed. Next the sensor framework has to be fitted around the belt. After that the sensor framework can be mounted in the subframe by two rods. Then the subframe can be mounted in the side-cover, see figure 2.2.

![Figure 2.2 The pushbelt speed measurement system mounted in the side-cover.](image)

Subsequently the inductive sensor can be adjusted compared to the segments of the pushbelt. This can be established as close as possible. After that the complete transmission-house can be put on the side-cover. For assembly the other parts the CVT has to be turned around, so that the side-cover points upwards. If the two bolts, with which the subframe is mounted, are removed, the side-cover can also be removed. Do not forget to fix the subframe in the side-cover again, with the two bolts.
2.2 The expected signal

Based on the pushbelt construction an estimation of the sensor signal can be made. The metal pushbelt consist of two sets of nine or twelve rings. These rings keep the segments together. This is shown in figure 2.3.

![Figure 2.3](image)

*Figure 2.3* Left the layout of a metal pushbelt and right the segment.

If the segments are pushed together there will be an airgap of minimal 0.3 mm between them. This gives the possibility to count the segments by a sensor. So the sensor needs a high operation frequency of at least two times the segment-pass frequency. Furthermore the sensor must be resistant against oil and high temperatures. To prevent friction and wear the sensor should not make contact the belt. The sensor type which is applicable is an inductive one with a permanent magnet inside. This magnet projects a magnetic field to the area immediately in front of the sensor. By every segment of the belt moving through this area the sensor generates an electric signal. By counting the segments during a certain time the pushbelt speed can be calculated.

To make a reliable estimation of the pushbelt speed, the sensor must be able to make distinction between the different segments that means that every airgap must be detected. During fine-tuning it appeared that the sensor has to be close near the belt, to obtain a useful block-signal.
Chapter 3

Unloaded measurements

The unloaded measurements are done by the Simulink model of Rob Pulles. This model is made especially for the CVT-CK2. In this model some parts are added for reading out the signal of the pushbelt speed sensor. After that the model is implemented in dSPACE. The dSPACE system will control all the components of the unloaded test rig.

3.1 Measurement conditions

To protect the pushbelt speed measurement system the angular speed of the primary pulley will not be more than 1000 revolutions per minute. This is done to assure that the oil pump generates enough flow. Also by the loaded measurements it is feasible for the motor Test Rig (TR3). During the tests the geometrical ratio is varied from Underdrive to Overdrive and back. Based on this data the minimal and maximal pushbelt speed can be calculated. The speed ratio can be calculated with the next formula:

\[
    r_s = \frac{\omega_s}{\omega_p}
\]

Where \( \omega_p \) represents the angular speed of the primary shaft and \( \omega_s \) the angular speed of the secondary shaft.

The theoretical belt speed can be found by:

\[
    v_s = \omega_s \cdot R_s
\]

In which \( R_s \) represents the radius position of the belt on the secondary pulley. This results in the table, that is shown below.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Minimal</th>
<th>maximal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_p )</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>( \omega_p )</td>
<td>104.72</td>
<td>104.72</td>
</tr>
<tr>
<td>( r )</td>
<td>0.43</td>
<td>2.25</td>
</tr>
<tr>
<td>( \omega_s )</td>
<td>45.03</td>
<td>235.62</td>
</tr>
<tr>
<td>( R_s )</td>
<td>0.079</td>
<td>0.034</td>
</tr>
<tr>
<td>( v_s )</td>
<td>3.56</td>
<td>8.20</td>
</tr>
</tbody>
</table>

Table 3.1 Expected belt speed by the unloaded measurements.
The theoretical belt speed is calculated by using the parameters of the secondary part of the variator, because the clamping force of the secondary pulley is always maximal. The clamping force \( F \) is generated by the hydraulics. The pressure of the secondary pulley cylinder is equal to the line pressure submitted by the pressure regulator valve, as shown in Appendix B. The pressure of the primary pulley will be adjusted by the shift control valve, which depends on the position of the steppermotor and on the position of the feeler at the moveable sheave. Slip between the belt and the secondary pulley is only possible in theory if \( F_s \cdot A_{b,s} < F_p \cdot A_{b,p} \). Where \( A_b \) represents the contact surface between the pushbelt and the primary or secondary pulley. The size of the contact surface depends on the running radius of the belt at the pulley.

### 3.2 Belt speed sensor signal

By moving the segment through the magnetic field of the sensor, the sensor generates an electric signal. By counting this signal during a certain time the pushbelt speed can be calculated. Figure 3.1 shows the belt speed sensor signal multiplied by the thickness of a segment. The thickness of a segment includes the airgap, so it is multiplied by 1.8 mm, see figure 2.3.

![Figure 3.1 Speed signal of the pushbelt speed sensor.](image)

The sensor not only generates the expected signal, but also noise (not white noise) as visibly in the figure above. For conditioning the sensor signal by a lower and upper boundary is based on the theoretical belt speed. The lower and upper boundary are determined at fifty percent of the sensor signal. The filter-script for conditioning the belt speed signal is shown in appendix C. In figure 3.2 the result is depicted.
After conditioning, the signal can be filtered by a second order low pass filter, with a bandwidth of 5 Hz. Then the belt speed looks like the expected theoretical belt speed by all the different imposed geometrical ratios, see figure 3.3.
Chapter 4

Belt slip speed

To know the slip behavior in the variator it is important to detect the slip as accurate as possible. The cause of the occurring slip at the pulley can be found if the clamping forces, pressures and radii are known.

4.1 Slipping pulley

The differences between the geometrical ratio and the speed ratio can be translated into slip speed, by calculating the speed difference between the primary and secondary pulley. This also includes ratio change caused by pulley deflection and belt elongation. This absolute pulley slip speed is defined as a relation between the primary \( v_p \) and secondary theoretical belt speed \( v_s \) \[2\]:

\[
v_d = v_p - v_s = \omega_p \cdot R_p - \omega_s \cdot R_s
\]

\[(3)\]

\( R_p \) and \( R_s \) are the running radii of the pushbelt at the primary and secondary pulley, and according to the geometrical ratio:

\[
r_g = \frac{R_p}{R_s}
\]

\[(4)\]

In case of pure primary pulley slip, the absolute pulley slip speed \( v_d \) will be equal to:

\[
v_{d,p} = v_p - v_{belt}
\]

\[(5)\]

Where \( v_{belt} \) represents the measured belt speed by the inductive sensor. The same applies to pure secondary pulley slip, in that case \( v_d \) will be equal to:

\[
v_{d,s} = v_s - v_{belt}
\]

\[(6)\]

The slip can be determined from figure 3.3. In table 4.1 can be seen if this slip occurs at the primary or secondary pulley.

<table>
<thead>
<tr>
<th></th>
<th>( v_p = v_s = v_{belt} )</th>
<th>( v_d = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No slip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slip at primary pulley</td>
<td>( v_d = v_s ) and ( v_p &gt; v_{belt} )</td>
<td>( v_d ) is negative</td>
</tr>
<tr>
<td>Slip at secondary pulley</td>
<td>( v_d = v_p ) and ( v_s &gt; v_{belt} )</td>
<td>( v_d ) is positive</td>
</tr>
</tbody>
</table>

Table 4.1 Explanation how slip becomes visible like figure 4.1.
The slip in the variator is defined as [3],[4]:

\[ \nu = 1 - \frac{r_s}{r_g} \]  

(7)

Substituting equation (1) and (4) the formula can be rewritten. This will give the next equation for the slip between the primary pulley and the belt:

\[ \nu_p = 1 - \frac{v_{belt}}{v_p} \]  

(8)

The slip between the secondary pulley and the belt is defined as:

\[ \nu_s = 1 - \frac{v_{belt}}{v_s} \]  

(9)

Both slip possibilities are depicted in figure 4.2.

The figures 3.3, 4.1 and 4.2 show that the belt at the primary pulley will always slip if the ratio goes from UnderDrive to OverDrive. But if the ratio goes from OverDrive back to UnderDrive the belt starts slipping at the secondary pulley till the desired ratio is reached. When this ratio is reached, there will be some slip at the primary pulley till the system is stabilized. After ratio 0.75 the belt starts slipping again only at the primary pulley.
4.2 Modeling

To condition the belt speed sensor signal, a Simulink model is made which is divided in two parts. The first part theoretical belt speeds in the variator are calculated and the measured belt speed is conditioned. In the second part the speed difference of the two pulleys and the slip in the variator is calculated. The used equations of the filter-script can be constructed in Simulink, resulting in the model shown in appendix D.

The model of the slip behavior is added in the Simulink model of the un- and loaded test rig for the CVT-CK2. After that the total model is implemented in dSPACE. So the dSPACE system controls all the components of the test rig.

Figure 4.2 The slip in the variator by different ratios.

Figure 4.3 The Simulink model of the slip behavior in the variator.
Chapter 5

Loaded measurements

The loaded measurements on the motor Test Rig (TR3) are also done by using an existing Simulink model. In that model the Simulink model of the slip behavior is implemented in the variator. A disadvantage of the used CVT-CK2 is that there is no Linear Variable Differential Transformer (LVDT) sensor mounted. So the actual position of the moving pulley sheave cannot be measured. Only the extremity positions of the moveable pulley sheaves, in Under- and OverDrive, are known. For that reason the loaded measurements will be done in this two extremity positions. During the measurements the load on the secondary axle will be increased (see appendix F.1) till the pushbelt slips at one of the pulleys.

Still it is possible to know the running radii at the ratios Under- and OverDrive by using the r2Rp-script, shown in Appendix E, instead of LVDT. This script will calculate the running radii of belt at the primary and secondary pulley by these imposed geometrical ratios.

5.1 Measurements in UnderDrive

To get repeatable data of the measurements the engine speed has to be constant. Therefore the engine speed of the TR3 will be controlled. At minimal line pressure the controller works well at 2200 revolutions per minute. The minimal line pressure makes it possible to see the slip behavior of the pushbelt in the variator by relative small loads.

By this engine speed the pushbelt speed will also be higher compared to the belt speed at ratio 0.43 at the unloaded measurements. As shown in figure 5.1 there is a little offset between the theoretical belt speeds and the measured belt speed by the inductive sensor. If the system reaches its maximum traction coefficient, the belt starts to slip. Looking at the figures 5.2 and 5.3 it seems like slip occurs in the intervals; 500 till 1200 and 1800 till 2100 seconds and at \( t = 1560 \) seconds. It can be seen from figure 5.1 that this is not the case. The speed of the primary pulley \( v_p \) is equal to the speed of the secondary pulley \( v_s \), which means that the belt cannot be slipping. Would slip occur than there should be more torque loss as usually. So \( T_s \) have to decrease, but that is not the case, as shown in Appendix F.2. At \( t = 2620 \) seconds, the decrease of torque is visible for a short period. This means that there will be some slip in the secondary pulley.

Some slip between the belt and the primary pulley is visible at the first 200 seconds and at \( t = 3050 \) seconds. From \( t = 3252 \) seconds the load will be too high and the belt slips only in the primary pulley. This is shown in the little plot of figure 5.1. After slip is established, the load is removed as soon as possible to protect the pushbelt and the
pulleys. The slip at the variable belt speeds after the 3252\textsuperscript{th} second is caused by the engine control. The control reacts too slow.

![Figure 5.1](image1.png) **Figure 5.1** The belt speeds by increasing load.

The absolute speed differences between the pushbelt and pulley, and between the pulleys are shown in figure 5.2. The maximal reached absolute pulley slip speed, at t = 3252 seconds, is 1.5 m/s. As can be seen the absolute speed difference between the belt and the secondary pulley is zero, there is no slip.

![Figure 5.2](image2.png) **Figure 5.2** The absolute slip speeds by increasing load.
The slip in the variator as calculated by formula (8) and (9) is shown in figure 5.3. The maximal reached slip is 21 percent.

![Figure 5.3 The slip by increasing load.](image)

The slip in the secondary pulley at $t = 2620$ seconds becomes 3 percent. The slip between the belt and the primary pulley at the first 200 seconds is almost 1.5 percent.

The running radii of the primary and secondary pulley are known by the imposed geometrical ratio. In UnderDrive the contact surface between the pushbelt and the primary pulley will be the smallest. But transmitting torque from the pulley to the belt is also dependent of the clamping force. The used CVT-CK2 has no pressure sensors, only the line pressure is measured, see figure 5.4. It is possible to make an estimation of the maximal clamping forces by:

$$F = p \cdot A$$

Where $p$ represents the line pressure and $A$ the cylinder surface area of the pulley. This results in the table that is shown below.

<table>
<thead>
<tr>
<th>Unit</th>
<th>primary</th>
<th>secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ [Bar]</td>
<td>10.10</td>
<td>10.10</td>
</tr>
<tr>
<td>$A$ [cm$^2$]</td>
<td>301.92</td>
<td>141.13</td>
</tr>
<tr>
<td>$F_{\text{max}}$ [kN]</td>
<td>30.49</td>
<td>14.25</td>
</tr>
</tbody>
</table>

Table 5.1 Estimation of the maximal clamping forces in UnderDrive.

At $t = 2620$ seconds the belt slips at the secondary pulley because $F_s \cdot A_{b,s} < F_p \cdot A_{b,p}$. This would be caused by a low line pressure which results in a lower clamping force.
The slip at the first 200 seconds is a result of small fluctuations of the primary angular speed, caused by the engine control. These fluctuations appear because the controller has a slow response. By increase of the load the effect of the controller is less disturbing. At $t = 3252$ seconds the traction coefficient between belt and primary pulley reaches its maximum value and the belt starts to slip.

![Figure 5.4](image) The line pressure by increasing load.

### 5.2 Further measurements

Further measurements were not possible because the pole tip of the sensor was worn down (see figure 5.5) by the pushbelt. This results in an insufficient magnetic field. The magnetic field is to count all segments accurately and the belt speed is no longer equal or near equal to the theoretical belt speed. For this problem an approximation should be found.

![Figure 5.5](image) Left the sensor tip after the measurements and right how a new sensor looks like.
Chapter 6

Conclusions

The pushbelt speed measurement system for the CVT-CK2 has proven itself. The mechanical parts make it possible to follow the displacements of the belt during up and down shifting. A remaining disadvantage is the extensive assembly method of the measurement system.

After conditioning and filtering the belt speed signal the measured speed gives a good estimation of the belt speed. To make slip behavior in the variator visible a real-time Simulink model is made.

The unloaded measurements show that the pushbelt will slip at the primary pulley if the ratio goes from UnderDrive to OverDrive. But if the ratio goes from OverDrive back to UnderDrive the belt starts slipping at the secondary pulley till the desired ratio is reached. When the ratio becomes smaller than 0.75 the belt starts slipping at the primary pulley.

The used CVT-CK2 has no Linear Variable Differential Transformer sensor and no pressure sensors. So the loaded measurements can only be put into effect in the extremity positions of the moveable pulley sheaves, namely Under- and OverDrive. If the traction coefficient between belt and pulley reaches its maximum value the belt starts to slip. The measurement in UnderDrive establishes that it results in primary slip.

One other disadvantage of the pushbelt speed measurement system is the inductive sensor. The pole tip of this sensor is sensitive to wear this result in an insufficient magnetic field and not each segment will be counted. So the belt speed is no longer equal or near equal to the theoretical belt speed. For this problem a solution should be found.
Bibliography


Appendix A

Working plan of the subframe
Appendix B

The actuator system of the CVT-CK2
Conditioning of the belt speed

function [v_p,v_s,v_b_i,vd,vd_p,vd_s,vs_p,vs_s] = conditioner(v_b,Rp,Rs,n_p,n_s,perL,perU)

%--------------------------------------------------------------------------
% INPUT:
% v_b  : measured belt speed                                          [m/s]
% Rp   : calculated radius of the primary axle (by r2Rp)              [m]
% Rs   : calculated radius of the secondary axle (by r2Rp)            [m]
% n_p  : measured number of revolutions of the primary pulley         [rpm]
% n_s  : measured number of revolutions of the secondary pulley       [rpm]
% perL : lower boundary of the relevant percentage data               [%]
% perU : upper boundary of the relevant percentage data               [%]
%--------------------------------------------------------------------------
% OUTPUT:
% v_p   : calculated primary belt speed                               [m/s]
% v_s   : calculated secondary belt speed                             [m/s]
% v_b_i : measured belt speed after conditioning                      [m/s]
% vd    : speed difference primary and secondary                      [m/s]
% vd_p  : speed difference primary and belt                           [m/s]
% vd_s  : speed difference secondary and belt                         [m/s]
% vs_p  : variator slip primary and belt                              [-]
% vs_s  : variator slip secondary and belt                            [-]
%--------------------------------------------------------------------------

wp = (2*pi/60)*n_p; %[rad/s]
ws = (2*pi/60)*n_s; %[rad/s]
v_p = wp.*Rp;
v_s = ws.*Rs;
vd = v_p-v_s;
v_d_p = v_p-v_b;
v_d_s = v_s-v_b;
vs_p = 1-(v_b./v_p);
vs_s = 1-(v_b./v_s);

% Signal conditioning
v_b_i = []; pL = perL/100; pU = perU/100;
for i = 1:length(v_b)
    if i == 1
        vbi = v_s(1);
    elseif v_b(i) < (pL*v_s(i))
        vbi = v_b_i(i-1);
    elseif v_b(i) > ((1+pU)*v_s(i))
        vbi = v_b_i(i-1);
    else
        vbi = v_b(i);
    end
    v_b_i = [v_b_i,vbi];
end
Appendix D

Simulink model for belt speed sensor
Belt speed model:

Theoretical belt speed model:

Measured belt speed model:
Slip model:

Absolute pulley slip model:

Relative belt slip model:
Appendix E

Calculation of the running radii

function [Rp, Rs, phi] = r2Rp(r_new, l_new, a_new)
%---------------------------------------------------------------
%          (c) 2002 TU/e
% auteur : ir. Bram Bonsen
% datum : 11 april 2002
% doel : bereken de straal van de pulleys (Rp[m],Rs[m]) aan de
%        hand van een overbrengingsverhouding (r=ws/wp=Rp/Rs),
%        de bandlengte L[m] en de pulleyafstand a[m].
%---------------------------------------------------------------
% INPUT:
% r : geometrical ratio (TUE)
% L : lengte band
% a : afstand tussen de assen van de pulleys
%---------------------------------------------------------------
% OUTPUT:
% Rp: straal primaire as
% Rs: straal secondaire as
%---------------------------------------------------------------
% L-2*a*cos(phi)=Rp*(pi+2*phi)+Rs*(pi-2*phi)
% phi=asin((Rp-Rs)/a) % linearisatie: phi=(Rp-Rs)/a;
% r=Rp/Rs
% taylor: cos(phi): cos(phi)=1-(1/2)*phi^2;
%---------------------------------------------------------------
% als r = 1, dan is de relatie singulier (a1=0), dus aparte berekening voor
% r=1:
% a1=(1/a_new)*(r_new-1).^2;
% a2=p1*(r_new+1);
% a3=2*a_new-l_new;

for p=1:length(r_new)
    if a1(p)==0
        Rs(p)=-a3/a2(p);
    else
        %abc formule
        Rs(p)=(-a2(p)+sqrt(a2(p)^2-4*a1(p)*a3))/(2*a1(p));
    end;
end;
Rp=Rs.*r_new;
phi=asin((Rp-Rs)./a_new);
Appendix F

Torque in UnderDrive

Figure F.1 The imposed brake torque of the recurrent brake.

Figure F.2 The torque measured at the primary and secondary axle.
Nomenclature and Acronyms

Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVT</td>
<td>Continuously Variable Transmission</td>
</tr>
<tr>
<td>TR3</td>
<td>Test Rig 3</td>
</tr>
</tbody>
</table>

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value [Unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cylinder surface area</td>
<td>$[\text{m}^2]$</td>
</tr>
<tr>
<td>$A_{b,p}$</td>
<td>Contact surface between belt and primary pulley</td>
<td>$[\text{m}^2]$</td>
</tr>
<tr>
<td>$A_{b,s}$</td>
<td>Contact surface between belt and secondary pulley</td>
<td>$[\text{m}^2]$</td>
</tr>
<tr>
<td>$F$</td>
<td>Clamping force</td>
<td>$[\text{N}]$</td>
</tr>
<tr>
<td>$F_p$</td>
<td>Primary clamping force</td>
<td>$[\text{N}]$</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Secondary clamping force</td>
<td>$[\text{N}]$</td>
</tr>
<tr>
<td>$R_p$</td>
<td>Primary belt running radius</td>
<td>$[\text{m}]$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Secondary belt running radius</td>
<td>$[\text{m}]$</td>
</tr>
<tr>
<td>$n_p$</td>
<td>Primary pulley angular speed</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Secondary pulley angular speed</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$p$</td>
<td>Line pressure</td>
<td>$[\text{Pa}]$</td>
</tr>
<tr>
<td>$p_p$</td>
<td>Primary pulley pressure</td>
<td>$[\text{Pa}]$</td>
</tr>
<tr>
<td>$p_s$</td>
<td>Secondary pulley pressure</td>
<td>$[\text{Pa}]$</td>
</tr>
<tr>
<td>$r_g$</td>
<td>Geometrical ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$r_s$</td>
<td>Speed ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>$[\text{s}]$</td>
</tr>
<tr>
<td>$v$</td>
<td>Relative belt slip</td>
<td>[-]</td>
</tr>
<tr>
<td>$v_{belt}$</td>
<td>Measured belt speed</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$v_d$</td>
<td>Absolute pulley slip speed</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$v_p$</td>
<td>Primary theoretical belt speed</td>
<td>$[\text{m/s}]$</td>
</tr>
<tr>
<td>$v_s$</td>
<td>Secondary theoretical belt speed</td>
<td>$[\text{m/s}]$</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value [Unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>Slip in the variator</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu_p$</td>
<td>Slip between the primary pulley and the belt</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu_p$</td>
<td>Slip between the secondary pulley and the belt</td>
<td>[-]</td>
</tr>
<tr>
<td>$\omega_p$</td>
<td>Primary pulley angular speed</td>
<td>$[\text{rad/s}]$</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>Secondary pulley angular speed</td>
<td>$[\text{rad/s}]$</td>
</tr>
</tbody>
</table>