Implementation of a Suzuki Electronically-controlled Continuously Variable Transmission in a Formula Student racecar

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DCT 2009.015

Bachelor Final Project

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Eindhoven, October, 2008

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Chapter 1

Introduction

In 2003 a team was started at the Eindhoven University of Technology to participate in the international Formula Student competition. The Formula Student competition is an international design competition in which students from all over the world design and compete with a single seater race car.

A concept of the transmission might be a continuously variable transmission (CVT). The advantage of a CVT is that there is no power interruption at the driven wheels unlike with a conventional stepped gear transmission. This means smooth corner entering and a higher acceleration than with a conventional gear box, particularly since the engine speed can be a kept at power-optimal level.

The Suzuki Electronically-controlled Continuously Variable Transmission (SECVT) is a commercially available CVT which is implemented in a Suzuki Burgman 650 motor scooter. The CVT is electro-mechanically actuated and uses a v-belt for the transfer of the engine feasibility for power.

The implementing the SECVT on a race car of University Racing Eindhoven (URE) is investigated in this Bachelor Final Project. A reversed engineering study should clarify the functionality of the CVT.
A 3D CAD model of the CVT is produced for a correct documentation of the parts of the CVT. Besides this, an analysis of the forces on the CVT belt is made to verify if the strength of the belt is sufficient in the present application. The actuation speed of the SECVT is tested on an unloaded test bench at the facilities of Drivetrain Innovations (DTI). Finally some recommendations are made to improve the performance of the CVT.

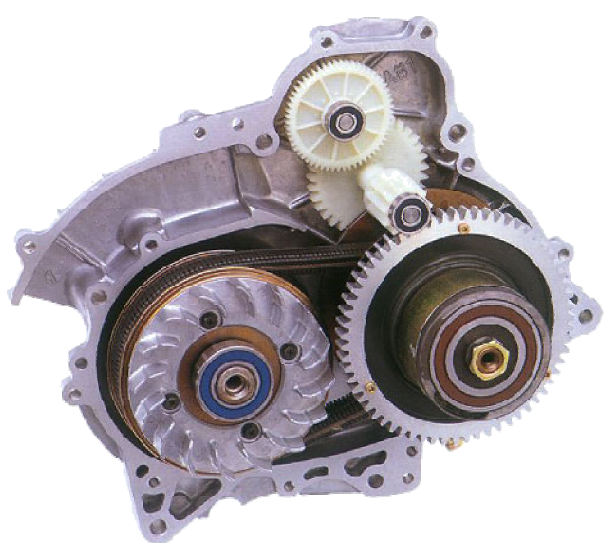


Figure 1.1: Suzuki Electronically-controlled Continuously Variable Transmission

Chapter 2

Suzuki Burgman 650

The driveline of a Suzuki Burgman 650 is equipped with a Suzuki Electronically-controlled Continuously Variable Transmission (SECVT). This CVT uses a set of variable diameter pulley sheaves. The CVT is electronically controlled with a control unit. A section of a part of the Burgman 650 driveline is shown in appendix A.

2.1 Driveline Suzuki Burgman 650

The driveline of a Burgman 650 consists of the following components:

Engine

55 hp (40.1 kW) @ 7000 rpm
62 Nm @ 5000 rpm

↓

Primary reduction

Reduction ratio ± 1.50

↓

CVT

Automatic transmission ratio:
Variable change (1.800 – 0.465)

↓

Clutch

Wet multi-plate automatic clutch
Centrifugal type

↓

Final reduction

Gear train
Reduction ratio 1.580 (32/31 x 31/32 x 34/31 x 49/34)

Chapter 3

Engine selection

To select the best power source for the race car, different engines had to be compared. Two different concepts are compared, bearing in mind that the engine for the race car has some restrictions within the Formula Student competition. The maximum diameter of the restrictor in the intake is 20 mm and the maximum cylinder volume is 610 cc.
The first concept is the implementation of a Suzuki Burgman 650 engine. The second concept is a Suzuki GSX-R 600 motorcycle engine. This engine is already used in race cars of University Racing Eindhoven.

3.1 Suzuki Burgman 650 engine

The specifications of the engine are shown in table 3.1.

Type	Four-stroke, Liquid-cooled, DOHC
Number of cylinders	2
Power	55.00 hp (40.1 kW) @ 7000 rpm
Torque	62.00 Nm @ 5000 rpm
Bore	75.5 mm (2.972 in)
Stroke	71.3 mm (2.807 in)
Piston displacement	638 cm^3 (38.9 cu. in)
Compression ratio	11.2 : 1
Fuel system	Fuel injection system
Starter system	Electric starter
Lubrication system	Wet sump

Table 3.1: Specifications of a Suzuki Burgman 650 engine [www.bikez.com]

The advantage of this engine is the connection of the engine with the CVT. The configuration of the Burgman 650 could be adopted.

There are also some disadvantages of this engine, namely:

- The engine produces over a wide rpm range a relative low power. This is not desirable for a CVT application in a race car.
- Engine not suitable for race applications. The engine is designed for city traffic and not for a race circuit. The parts of the engine are not designed for high power production under all circumstances on the race track.
- Cylinder volume of the engine is 638 cc. This exceeds the competition rule of maximum 610 cc cylinder volume. The engine needs to be modified to conform to this regulation.

3.2 Suzuki GSX-R 600 engine

The specifications of the original engine and the modified restricted version are shown below in table 3.2.

	Original version	**Modified restricted version**
Type	Four-stroke, Liquid-cooled, DOHC	Four-stroke, Liquid-cooled, DOHC
Number of cylinders	4	4
Power	115.00 hp (85.8 kW) @ 13000 rpm	80.72 hp (59.36 kW) @ 11000 rpm
Torque	69.00 Nm @ 10800 rpm	65.67 Nm @ 8000 rpm
Bore	67.0 mm (2.6 in)	67.0 mm (2.6 in)
Stroke	42.5 mm (1.7 in)	42.5 mm (1.7 in)
Piston displacement	599 cm³ (38.9 cu. in)	599 cm³ (38.9 cu. in)
Compression ratio	12.5 : 1	13.0 : 1
Fuel system	Fuel injection system	Fuel injection system
Starter system	Electric starter	Electric starter
Lubrication system	Wet sump	Dry sump

Table 3.2: Specifications of a Suzuki GSX-R 600 engine [www.bikez.com]

The power of the modified engine is measured at the engine test bed of University Racing Eindhoven. An M-file is created (appendix B) to calculate the power of the engine at the crankshaft. An assumption of a drive train efficiency of 92 % is taken into account, because the power is measured at the driveshaft. Figure 3.1 shows the power and torque of the engine.

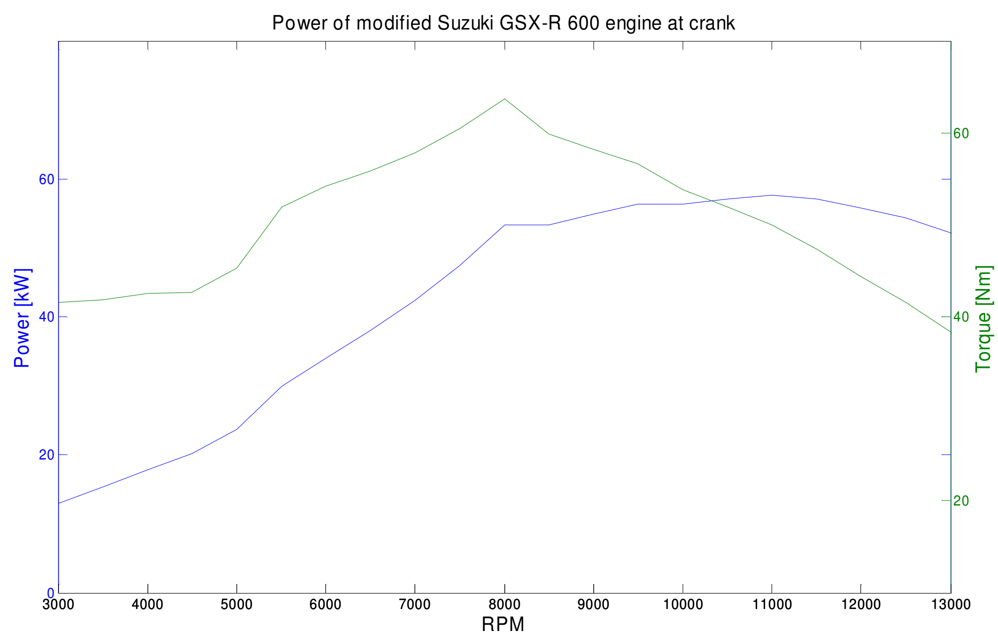


Figure 3.1: Figure of modified Suzuki GSX-R 600

The advantages of this engine are:

- High power of the engine, even with the restriction.
- Lot of knowledge of the engine in the team.
- Dry sump lubrication system (modified version). With the high lateral forces on the car, a dry sump system is more suitable for a race car application. This ensures there is oil pressure under all circumstances. With the system, the height of the engine is reduced which is beneficial for the center of gravity of the car.
- Suitable for race applications. The engine is used in several race competitions over the world.

A disadvantage of this engine choice is the unfamiliar connection of the CVT to the engine. This needs be designed and manufactured. Another problem could be the higher power (60 kW instead of 40 kW) that needs to be transmitted with the CVT belt. This could mean failure or excessive wear of the belt.

3.3 Engine choice

The Suzuki GSX-R 600 engine is chosen over the Burgman 650 engine for the driveline of the race car. The high power output and the experience with the engine are the reasons for this choice.

The necessary modifications of the Burgman 650 engine to conform the regulation for the competition where also a problem in the short time period of the design of the car.

Chapter 4

Suzuki Electronically-controlled Continuously Variable Transmission (SECVT)

4.1 Functioning of a CVT

The principle of a CVT is transmitting torque by friction (friction between the pulley sheaves and the belt) over an infinite number of ratios. By squeezing the belt between the pulleys, torque can be transmitted by tension or compression forces in the belt. The SECVT is equipped with a tension belt.
The ratio of a belt CVT is defined by the pitch radius on which the belt runs on each of the pulleys. The position of the pulleys can be adjusted gradually between the minimum and maximum setting, every possible ratio between the minimum and maximum setting can be achieved and used.

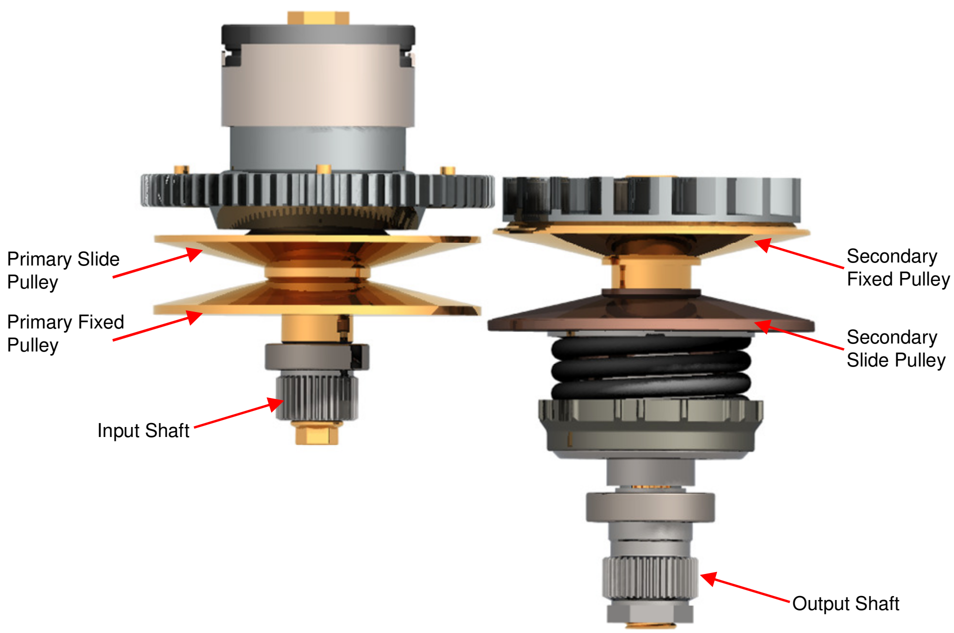


Figure 4.1: Top view of SECVT

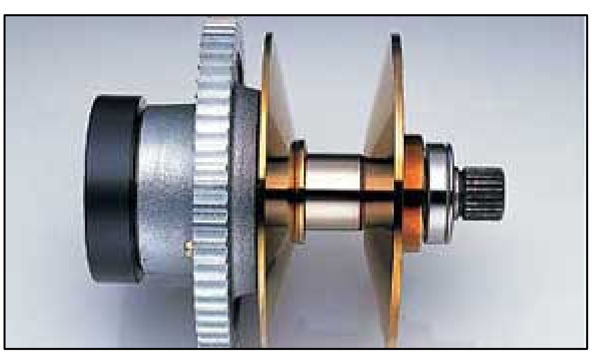


Figure 4.2: Primary pulley assembly (open)

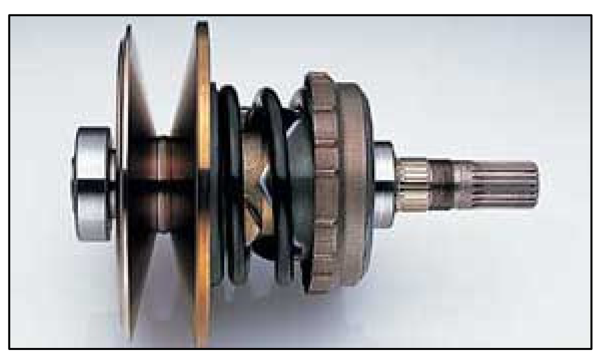


Figure 4.3: Secondary pulley assembly (closed)

4.2 Ratio changing mechanism

The ratio of a CVT is controlled by changing the distance of the pulley sheaves and thus the radius over which the belt runs. Moving a pulley sheave inwards or outwards is achieved by actuating the movable pulley sheaves.
The SECVT uses an electric motor that actuates the primary slide pulley sheave in an electro-mechanical way. The secondary pulley will follow the displacement of the primary pulley because of a spring that is incorporated in the design of the secondary pulley. The primary pulley is fitted with a spindle which is driven by a DC-motor and two plastic gears (figure 4.4). The total gear reduction for this mechanism is 1: 90.85; the spindle involves a reduction by altering a rotational movement into a translating movement. The size of this reduction causes the ratio changing system to be self breaking, meaning if the DC-motor is not powered, the spindle will maintain its position and thus the ratio of the SECVT remains the same.

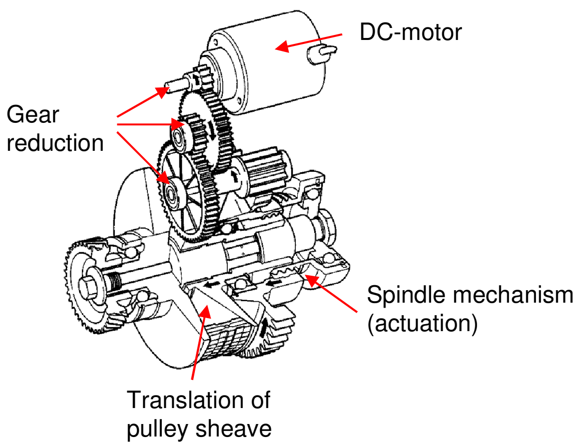


Figure 4.4: Actuation mechanism SECVT

As mentioned before, the secondary pulley (figure 4.5) is equipped with a spring which allows this pulley to follow the ratio change of the primary pulley. The spring in the secondary pulley also ensures the clamping force from the pulley sheaves to the belt (ratio dependent). The torque-cam mechanism of the secondary pulley is able to increase the clamping force if a torque peak is detected from the output shaft of the SECVT. The torque cam inside this pulley allows the pulley to increase the clamping force is enlarged due to the slope and friction material on the sliding surface. This mechanism allows the SECVT to be controlled fairly simple.

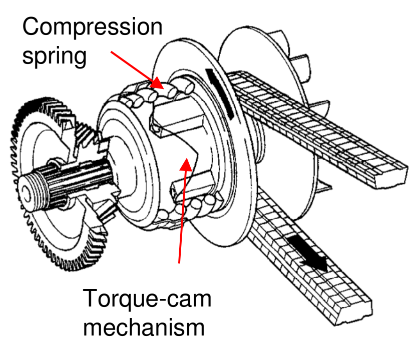


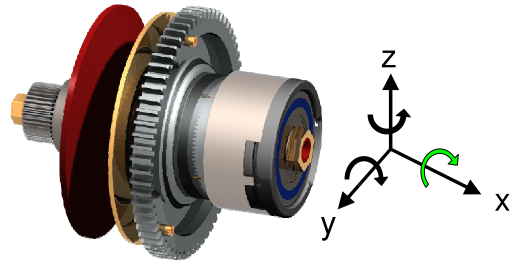
Figure 4.5: Torque-cam mechanism secondary pulley SECVT

4.3 Degrees of freedom (DOF)

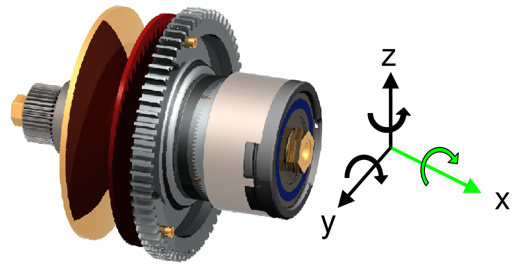
Every part of the SECVT has its own degrees of freedom. Below is explained what the DOF are for the different components (component shown in red) (DOF in green).

Primary pulley

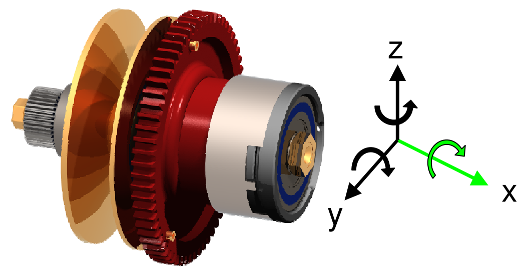
- Primary fixed pulley
  - Rotation around x-axis



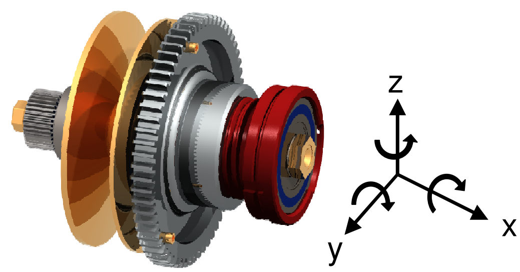
- Primary slide pulley
  - Rotation around x-axis
  - Translation along x-axis
  - Pulley sheaves rotate at same speed



- Primary slide pulley gear (when actuated)
  - Rotation around x-axis
  - Translation along x-axis

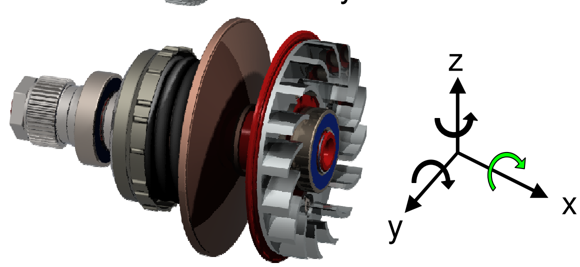


- Screw shaft
  - Fixed to housing

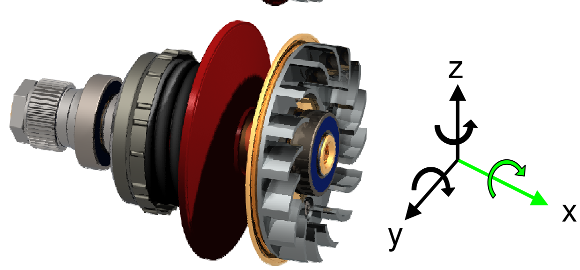


Secondary pulley

- Secondary fixed pulley
  - Rotation around x-axis



- Secondary slide pulley
  - Rotation around x-axis
  - Translation along x-axes
  - Pulley sheave can rotate independent within the limitations of torque-cam mechanism (*chapter 8*)



Chapter 5

3D CAD model of the SECVT

To study to functioning of the CVT, it is disassembled at the workshop of University Racing Eindhoven. A 3D model of the SECVT is made with the computer program UGS NX 5.0. The specifications of the specific parts are documented in appendix F. The number of the parts in appendix C.4 is related to the numbers in appendix C.1, C.2 and C.3.

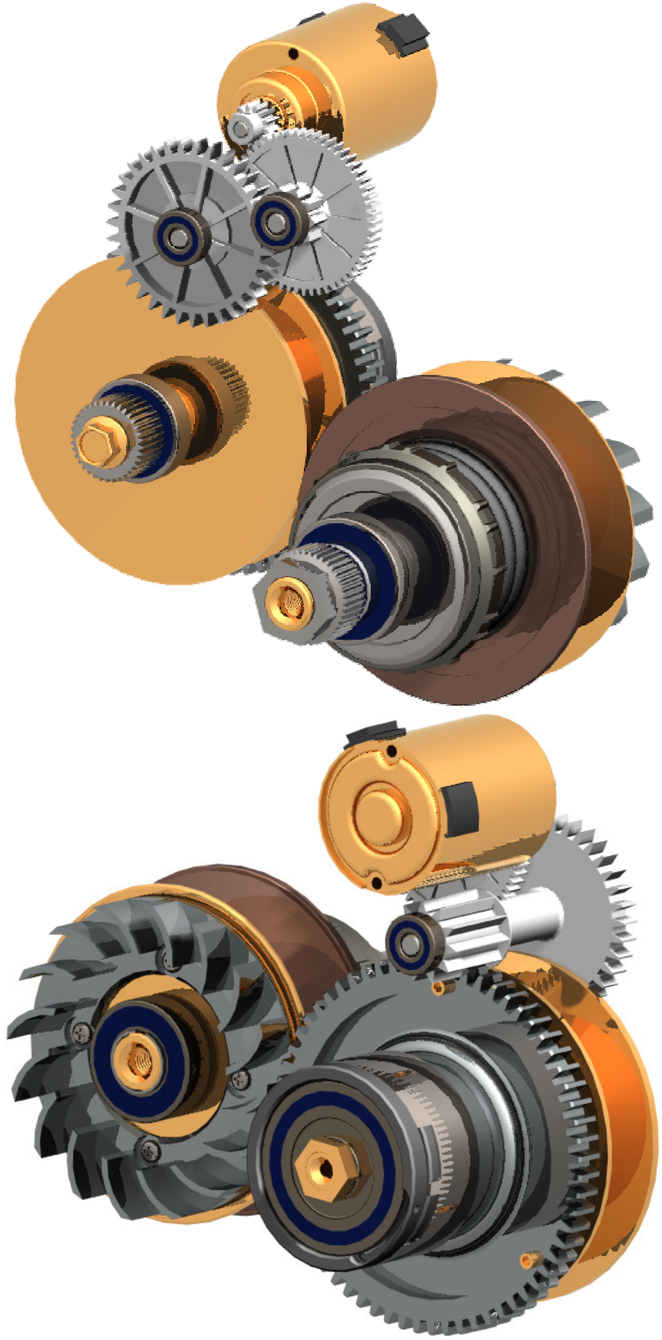


Figure 5.1: Side views of 3D CAD model of SECVT

Chapter 6

Efficiency of the SECVT

In order to get a high performance driveline of the car it is important to know the efficiency of the CVT. At the Technical University of Eindhoven (TU/e) experimental research is performed to determine the efficiency of the SECVT [*Study on the efficiency of an A-CVT*].

6.1 Measurement of the efficiency

The CVT is tested for certain ratios on a loaded test bench. Torque and angular velocity is measured at the in- and output shaft of the CVT. After data processing the efficiency of the transmission can be calculated by using equation 6.1.

$$\eta_{transmission} = \frac{P_{out}}{P_{in}}$$ *Equation 6.1*

$$P_{in} = \omega_{primair} \cdot T_{primair}$$ *Equation 6.2*

$$P_{out} = \omega_{secondair} \cdot T_{secondair}$$ *Equation 6.3*

This will give the efficiency of the system. The results of these measurements, more specific the efficiency of the transmission can be seen in figure 6.1.

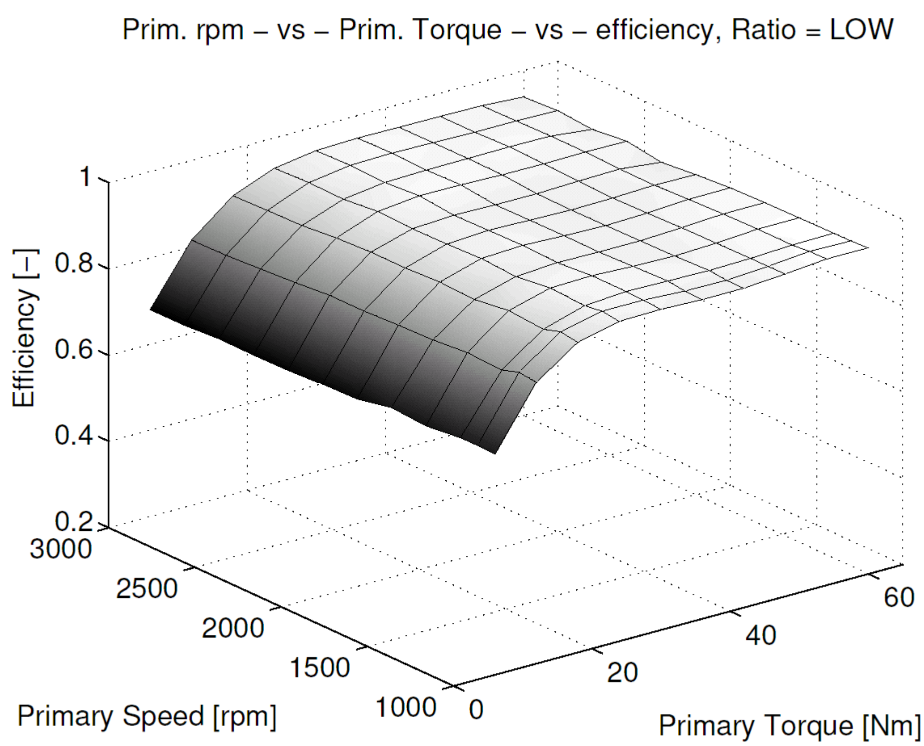


Figure 6.1: Efficiency of SECVT at ratio low

In figure 6.1 the efficiency is shown for the lowest CVT ratio. In this case the efficiency is between 92 % and 95% when the primary torque is more than 20 Nm.
In the application of a race car the primary torque is always higher than 20 Nm when power is applied on the CVT.
For other ratios the efficiency is shown in appendix D. It shows that the efficiency of the CVT is about 90% for most cases. For medium ratio the efficiency reaches even 95% for the majority of the torque span. At overdrive ratio the efficiency drops, because of higher friction in bearings and over clamping of the belt (*chapter 8*).

6.2 Race car application

On track test results have to show whether the efficiency of the SECVT is high enough to achieve higher performance than the stepped gear transmission in the race car.

Chapter 7

CVT Belt

The belt which is used in the SECVT is a design of Bando Chemicals and is developed as the next generation v-belts for heavy duty use in automotive applications and is called the Bando AVANCE.

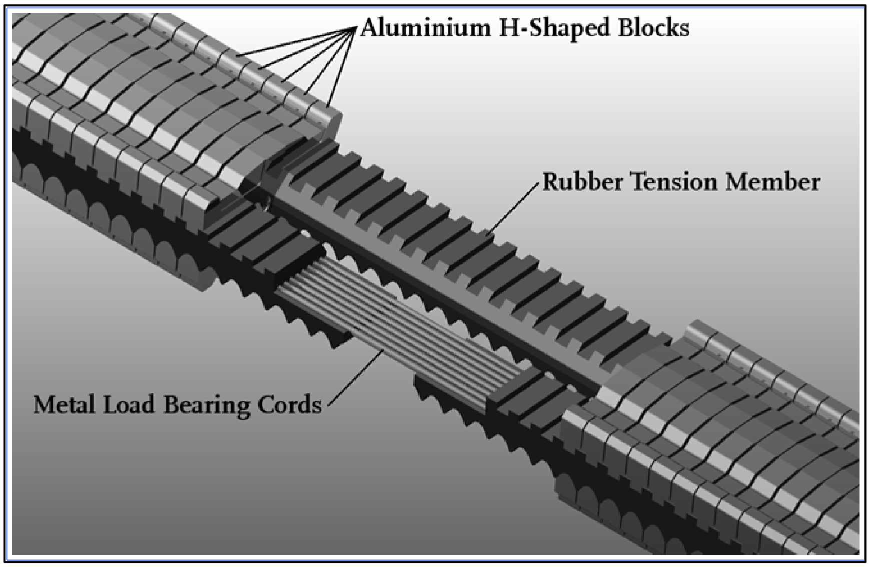


Figure 7.1: Section of the Bando AVANCE belt

7.1 Bando AVANCE

The belt consists of blocks and tension members which are displayed in figure 7.1. Since the dry hybrid v-belt is used as a pull belt, the transmission of power from the primary pulley to the secondary pulley is done by a surplus of pull forces in the belt. When pulling the blocks alone, no power can be transmitted. This means that the force has to be directed through the blocks to the belt at the primary pulley. This is done by creating notches in the tension members in which the blocks grip the tension member and transmit the force and vice versa at the secondary pulley.
The blocks are made of an aluminum core since they have to transmit power from the pulley sheave to the belt. This means that a certain thrust force has to be used to do so. The aluminum core of the blocks ensures the strength of the belt when clamping the belt while the aramid cords ensure the tensile stiffness of the belt. The required clamping force on the belt is limited because a friction material is added to the blocks and to the surface of the belt. This and the fact that no lubrication oil is used, causes the friction coefficient to increase and the required thrust to decrease at a certain transmittable torque. Therefore the required thrust on the dry hybrid belt is not as high as the thrust force on a conventional metal belt that is combined with an oil lubricated environment.

To improve the contact between pulley surfaces and the belt even more, the pulleys are treated with non-electrolyte Ni-P plating so that a good friction coefficient, abrasion, resistance and rust resistance is achieved. This layer causes the pulley and the friction coefficient to be sensitive to damage or wear. When damage is inflicted to this surface, it can be assumed that the torque cam mechanism is no longer capable of applying sufficient thrust force to the pulley-belt contact to transmit the applied power to or from the belt.

7.2 Limitations of the belt

To ensure a good lifetime of the belt, the manufacturer has introduced some limitations of the belt. The maximum speed of the belt is approximately 40 m/s and the maximum applied torque is 135 Nm (appendix C.5).
When the SECVT is used in combinations with the Burgman 650 engine, these limitations are not a problem. In the case that the modified Suzuki GSX-R 600 engine is applied the limitations could be a problem. When the speed of the belt is more than 40 m/s there can be assumed that the belt will slip (> 1%) between the pulley surfaces. This increases heat development in the belt which cause more wear of the belt.
To ensure that the speed of the belt will be below the limitations, the optimal primary reduction is 2.2724 (out/in). In this case the maximum speed of the belt is 40 m/s and the maximum applied torque on the belt is above 140 Nm. This will probably cause more wear to the belt, but not a failure of the belt. Manufacturers normally apply safety factors to ensure a long lifetime of the product. Therefore we trade higher torque transfer with lower lifespan of the belt. It has to be researched what the lifetime reduction will be in case of (sustained) overloading. At maximum input power, however, the torque is substantially lower than 135 Nm.

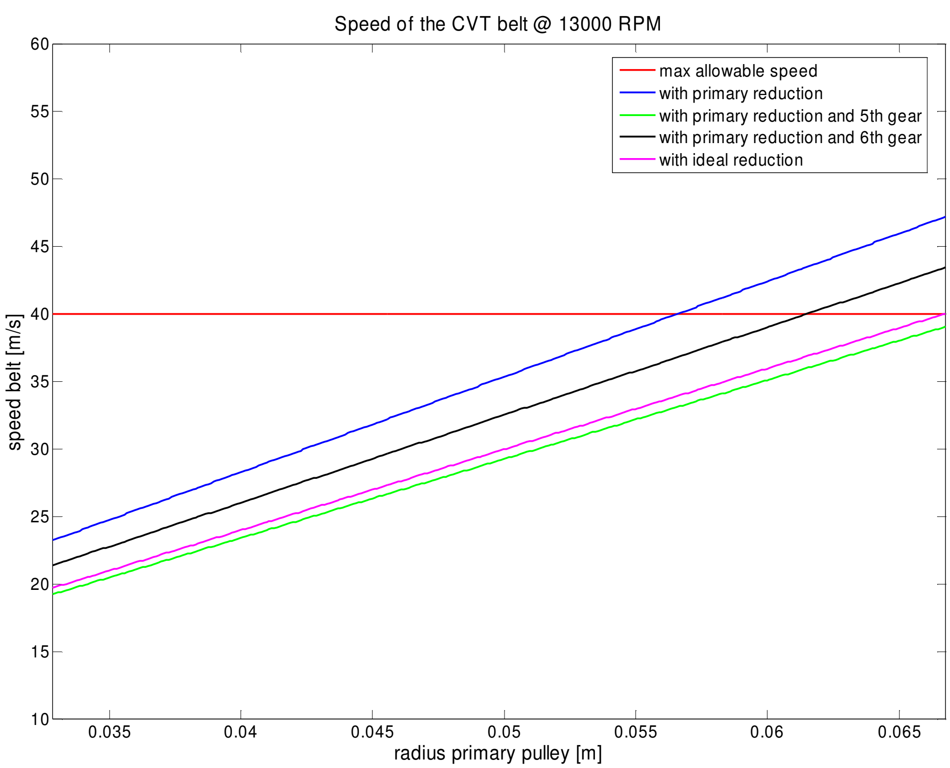


Figure 7.2: Speed of the CVT belt at different primary reductions

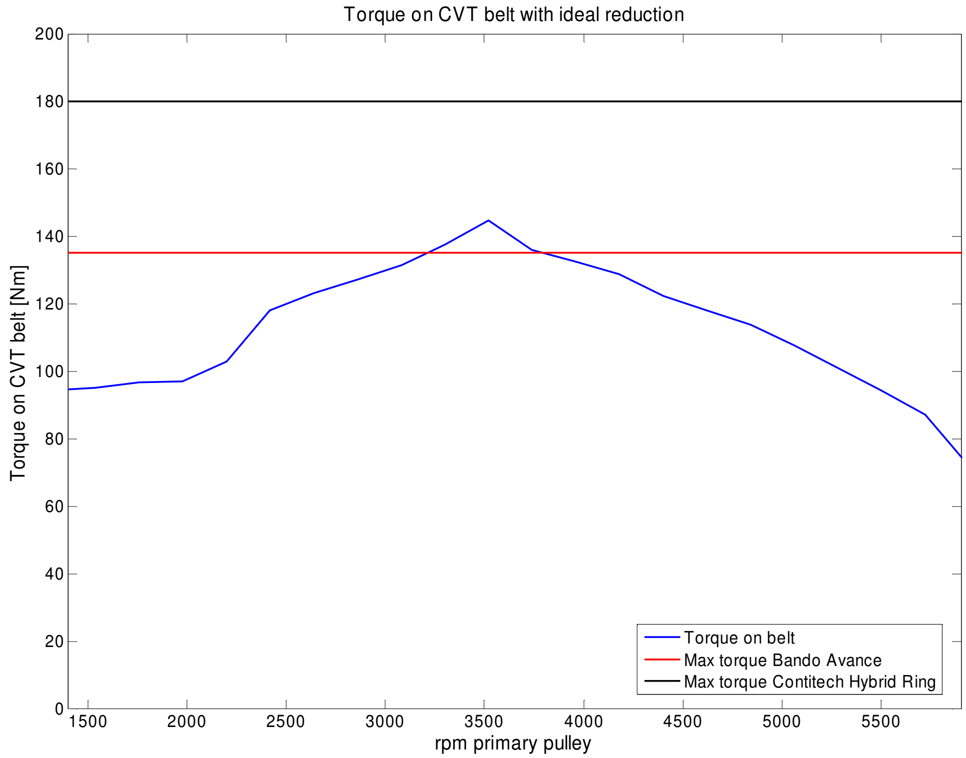


Figure 7.3: Torque on the CVT with the ideal primary reduction

7.3 Contitech Hybrid Ring

Contitech (division of Continental) has announced a new type of hybrid belt. This belt has the same dimensions as the Bando AVANCE, but the maximum allowed torque is much higher. The permitted torque is 100 to 130 Nm. The belt can withstand torque peakes up to 180 Nm. This while the efficiency of the CVT (belt and pulley sheaves) is 90-95 %. The belt is not yet commercialy available (only for OEM evaluation).

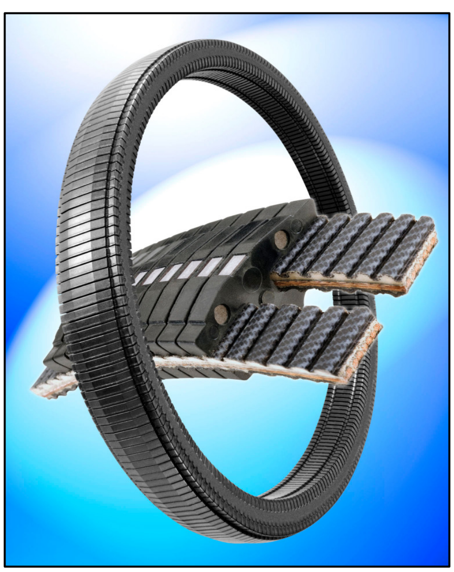


Figure 7.4: Contitech Hybrid Ring [www.contitech.de]

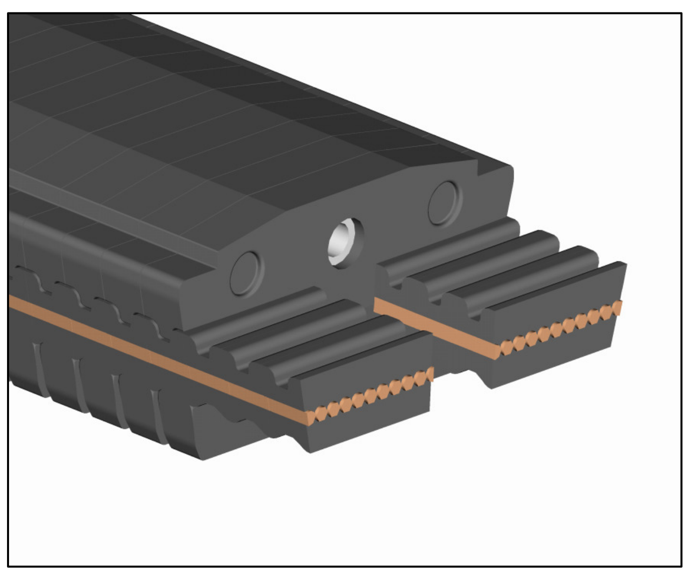


Figure 7.5: Section of Contitech Hybrid Ring [www.contitech.de]

Chapter 8

Thrust force of the SECVT

The thrust force in the SECVT is generated by two components namely the spring and the torque-cam in the secondary pulley. The primary pulley forces the belt to run on a certain running radius at the primary pulley as on the secondary pulley. This implies that each speed ratio cause a fixed thrust force of the spring. This thrust force is increased by making use of the torque-cam. At a certain load the cam will press against the follower, causing an additional thrust force on the belt.

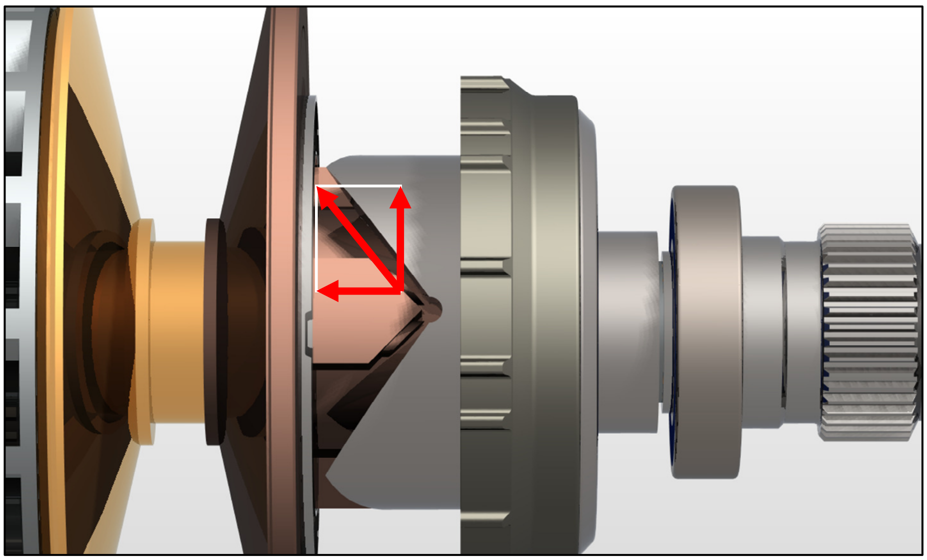


Figure 8.1: Forces of torque cam in secondary pulley

The graph in figure 8.1 shows the thrust force in relation to the applied torque and ratio. The calculations of the thrust force can be found in appendix F. The additional thrust force generated by the torque-cam is only dependant on the applied torque and not of the present ratio. This could mean that the safety factor in high gear will be very high when transmitting a low torque. This forces the efficiency to decrease when transmitting a fixed input torque and speed while shifting towards high gear.
The modified Suzuki GSX-R 600 engine produces a lot more torque in comparison to the original Burgman 650 engine. This causes that the thrust force is a lot higher in comparison to the Burgman 650 engine. When over clamping occurs energy is dissipated in the belt and thus not reaching the output shaft of the CVT. This could mean a lower efficiency of the CVT or increased wear of the belt. Extensive testing of the CVT on a loaded test bench could evaluate this.

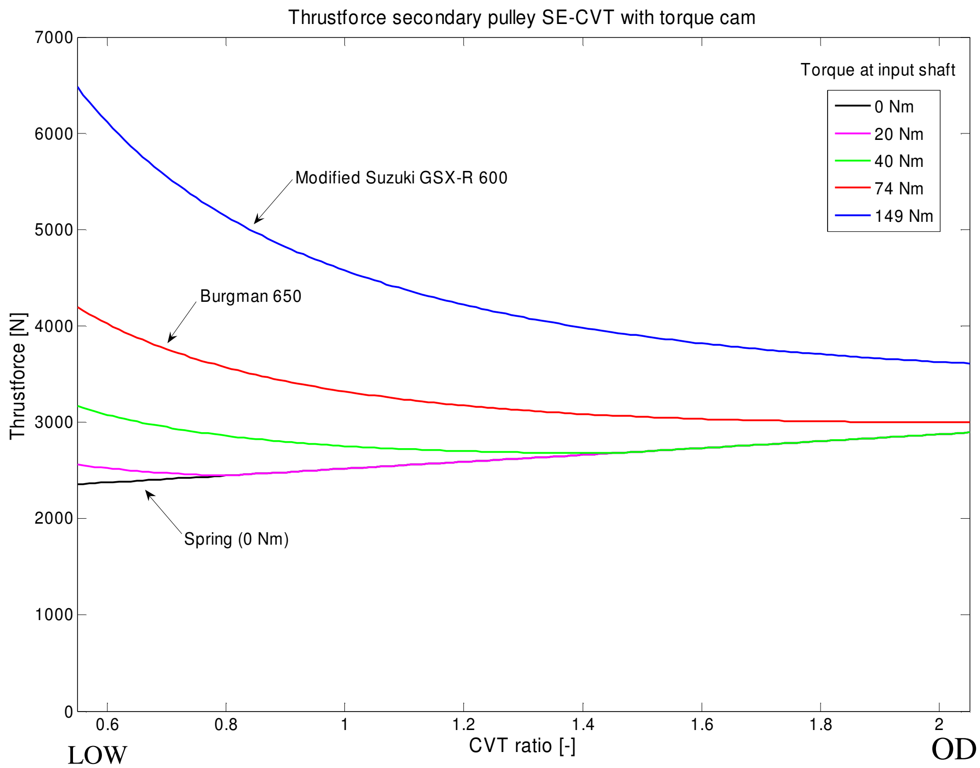


Figure 8.2: Thrust force of the secondary pulley on CVT belt

Chapter 9

Cooling of the SECVT

The efficiency of the SECVT is less than 100%. The energy that is not transmitted with the CVT belt will be converted into heat. To ensure that the heat will be diverted swiftly to the surroundings, a cooling system is implemented.

A build-in fan will create airflow in the SECVT. An air duct at the front side of the Burgman 650 motor scooter channels air to the fan of the CVT. Figure 9.1 shows schematically the flow that is created with the fan. A cochlea circulates the air flow in the CVT casing and pushes the heated air out of the CVT casing.

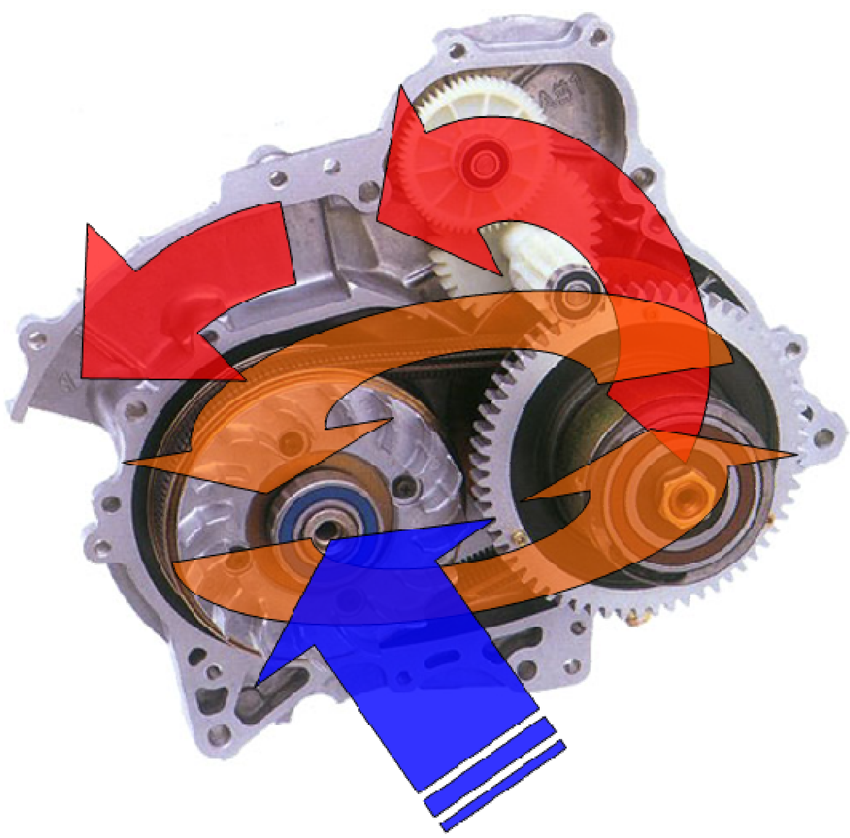


Figure 9.1: Schematically representation of the flow in the CVT casing

Chapter 10

Control of the CVT

The SECVT is electronically controlled with a control unit. This control unit is incorporated in the ECU of the Burgman 650. The unit controls the CVT motor which actuates the primary slide pulley.
Different sensors are connected with the control unit. Figure 10.1 is a schematic presentation of the functioning of the CVT control unit. The CVT primary pulley position and CVT secondary pulley revolution sensor are incorporated in the casing of the SECVT.

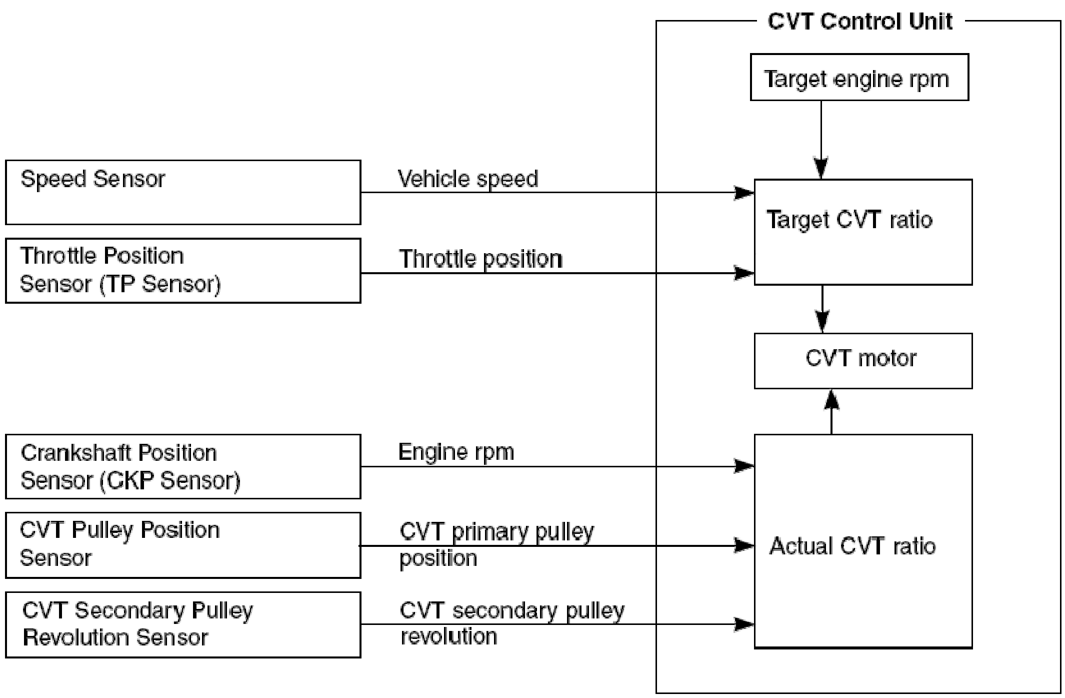


Figure 10.1: Overview of the functioning of the control unit of the SECVT

10.1 CVT primary pulley position sensor

For the control strategy of the ratio change mechanism, a pulley position sensor is used to measure the presence of slip in the CVT. This is necessary since the dry hybrid v-belt is not allowed to slip for more than 1% over a period, longer than a few seconds. If this happens, permanent damage can be done to the belt. The pulley position sensor is non-linear axial displacement sensor. The contact surface between the sensor and the pulley does rotate but only when the ratio is changed and even then at a low rotational speed. This means that the influence of this rotating surface is a low and that the contact is maintained which allows a correct read out of the sensor. The contact between the sensor tip and the gear is ensured by a spring which is incorporated in the design of the sensor.

Specifications sensor:

- non-linear axial displacement sensor
- 0.06 V ≤ sensor voltage ≤ 5.04 V
- Input voltage: 4.5-5.5 V
- Resistance: Compressed: 1.9-2.3 kΩ
Extended: 0.2-1.0 kΩ

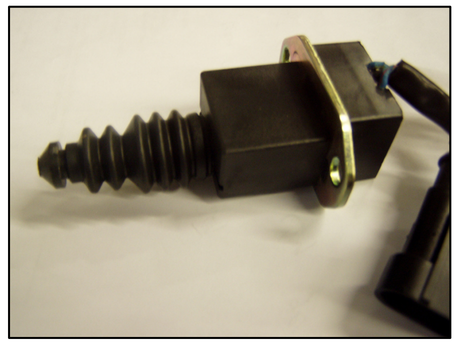


Figure 10.2: Primary pulley position sensor

10.2 CVT secondary pulley revolution sensor

The speed sensor which is used in the transmission for control purposes is an inductive pulse sensor which is combined with 18 notches in the secondary pulley. A speed sensor at the primary pulley is not available in the transmission since the primary pulley speed is obtained by measuring the crankshaft speed and multiplying it with gear reduction in between.

Specifications sensor:

- inductive pulse sensor
- 18 notches on secondary pulley
- input voltage: > 7 V
- resistance: 400-600 Ω
- sensor peak voltage : > 5 V (idle speed)
- effective range: 0.38 – 3.62 V

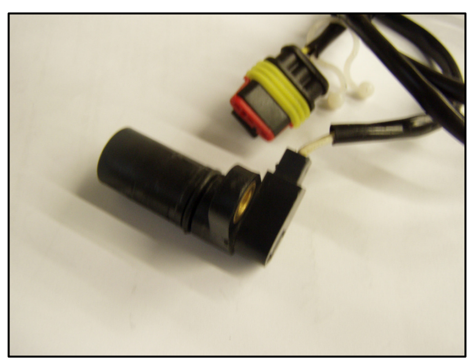


Figure 10.3: Secondary pulley revolution sensor

Chapter 11

Measuring of the shift speed

To determine if the shift speed of the SECVT is sufficient for the application of a race car, measurements are done. The shift speed of the CVT is measured on an unloaded test bench at Drivetrain Innovations (DTI) (figure 11.1).
The test bench consists of an electric motor which is capable of maximum 3000 rpm. The maximum allowed revolutions per minute of the CVT is higher as this value, but the specification of the electric motor is sufficient to test the functioning of the CVT.
The outgoing shaft of the electric motor is connected to the CVT with an adapter (appendix G.1) which is custom made at VDL.
The data acquisition that is used for the measurements is D-space.

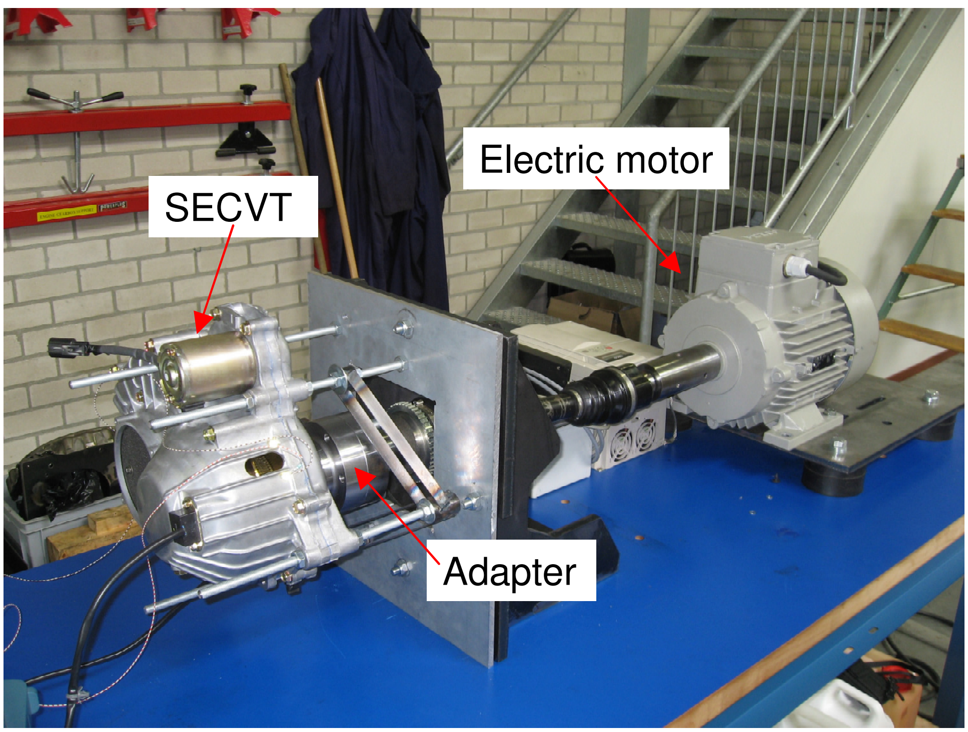


Figure 11.1: SECVT on unloaded test bench of Drivetrain Innovations

11.1 Wiring of the set up

The first step of building the measuring set up is to connect the computer interface with the sensors of the test bench. A schedule of the wiring of the set up can be seen in appendix G.2.

11.2 Calibration of the pulley position sensor (PPS)

To achieve correct test results, the PPS has to be calibrated. The displacement of the sensor is measured with a micrometer. At the same time the outgoing voltage of the sensor is measured. The measurements are done three times, to ensure that the calibration is correct (table 11.1).
With Matlab a polyfit is made (appendix G.3). The average data is used in a look up table in the D-space environment.

Compression PPS [mm]	Measurement 1 [V]	Measurement 2 [V]	Measurement 3 [V]	Average [V]
0	0,142	0,142	0,142	0,142
1	0,235	0,226	0,241	0,234
2	0,358	0,347	0,364	0,356
3	0,485	0,478	0,491	0,485
4	0,632	0,623	0,628	0,628
5	0,771	0,747	0,777	0,765
6	0,911	0,883	0,991	0,928
7	1,06	1,03	1,06	1,050
8	1,21	1,18	1,19	1,193
9	1,35	1,34	1,34	1,343
10	1,55	1,53	1,53	1,537
11	1,75	1,73	1,76	1,747
12	1,97	1,96	1,98	1,970
13	2,2	2,18	2,19	2,190
14	2,43	2,41	2,46	2,433
15	2,73	2,72	2,72	2,723
16	3,03	3,05	3,04	3,040
17	3,39	3,4	3,4	3,397
18	3,81	3,8	3,8	3,803
19	4,32	4,3	4,28	4,300
20	4,82	4,82	4,82	4,820

Table 11.1: Calibration of the PPS sensor

11.3 D-space environment

In D-space an environment is created to control the DC motor of the SECVT and to obtain the sensor outputs of the test rig. The environment is shown in figure 11.2.

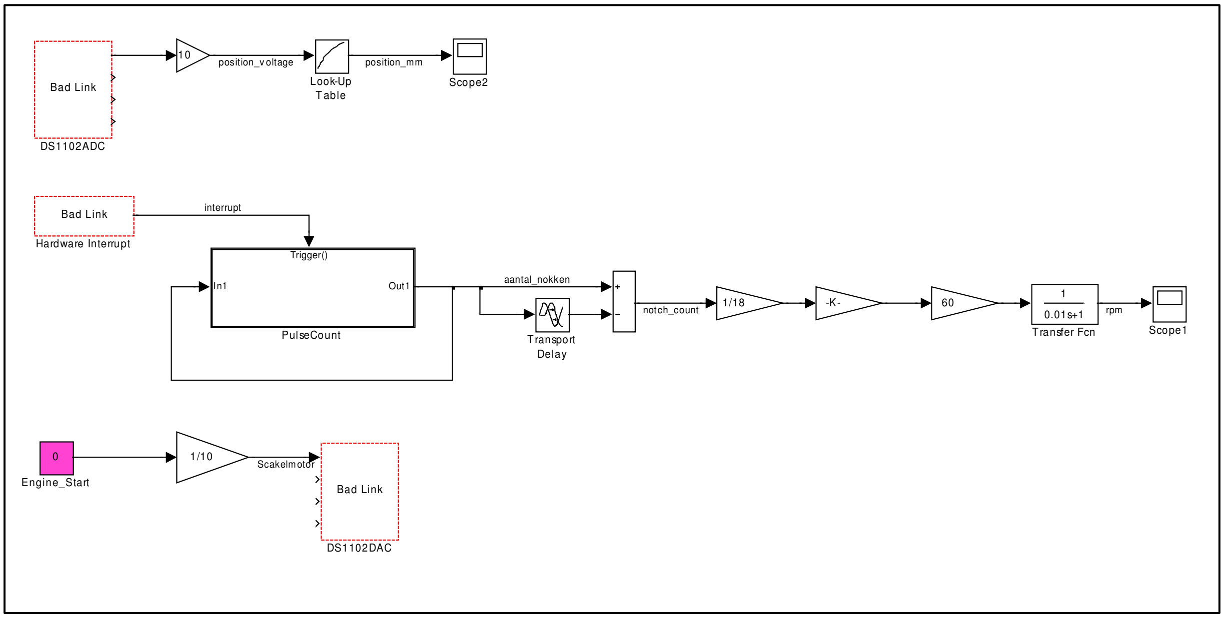


Figure 11.2: D-space environment

11.4 Problem with secondary pulley revolution sensor

During the test a problem encountered with the secondary pulley revolution sensor. D-space could not process the data of the sensor. Warnings were shown on the screen, because there were problems with overflows. Measurement showed that correct data was received in D-space, but when the data was logged to an outgoing file, problems occurred. There is decided to ignore the problem and finish the test without the data of the sensor.

11.5 Data processing

An M-file is created to process the received data (appendix G.4). Because of the problem with the secondary pulley revolution sensor, the rpm of the secondary pulley is calculated with the data of the primary pulley position sensor. With the data of the primary pulley position sensor the CVT ratio is calculated. Together with the rpm of the primary pulley, the rpm of the secondary can be determined.

11.6 Analyzing results

The final step is analyzing the test results. The revolutions per minute of the primary pulley are remained constant at 1000, 2000 and 3000 rpm. Every measurement is done five times, to verify if the results change per measurement. Figure 11.3 shows the compression and voltage of the pulley position sensor. Figure 11.4 shows the rpm of the primary and secondary pulley while the CVT shifts down in its ratio. You can see that the rpm of the primary pulley is constant (1000 rpm) and the rpm of the secondary pulley is changing. The time that the CVT shifts down in its ratio change is approximately 1.45 s. This value does not change for different rpm of the primary pulley (table 11.2). The figures of the data of the measurements at 2000 and 3000 rpm of the primary pulley can be found in appendix G.5. The figures in the appendix show that the shift time does change while shifting up for different motor speeds of the primary pulley (see also table 11.2).

An explanation is that a higher force is required to move the secondary pulley against the direction of the compression spring. While downshifting this works in the opposite direction and it is an advantage. Besides that a race car decelerates faster than it accelerates, so a shorter downshifting time is good for the implementation of the SECVT in a Formula Student race car.

Another thing that changed was the current of the power supply of the DC motor (peak values of 20 A). When the pulleys rotate at higher speeds it is easier to alternate the ratio. Therefore the current of the CVT motor drops at higher rotational speeds while the voltage is constant. What can be expected out of the measurements is that the current of the CVT motor will drop more if the input speed is higher. The nominal input speed in a Formula Student race car is around 5500 rpm. This also decreases the shift time of the CVT.

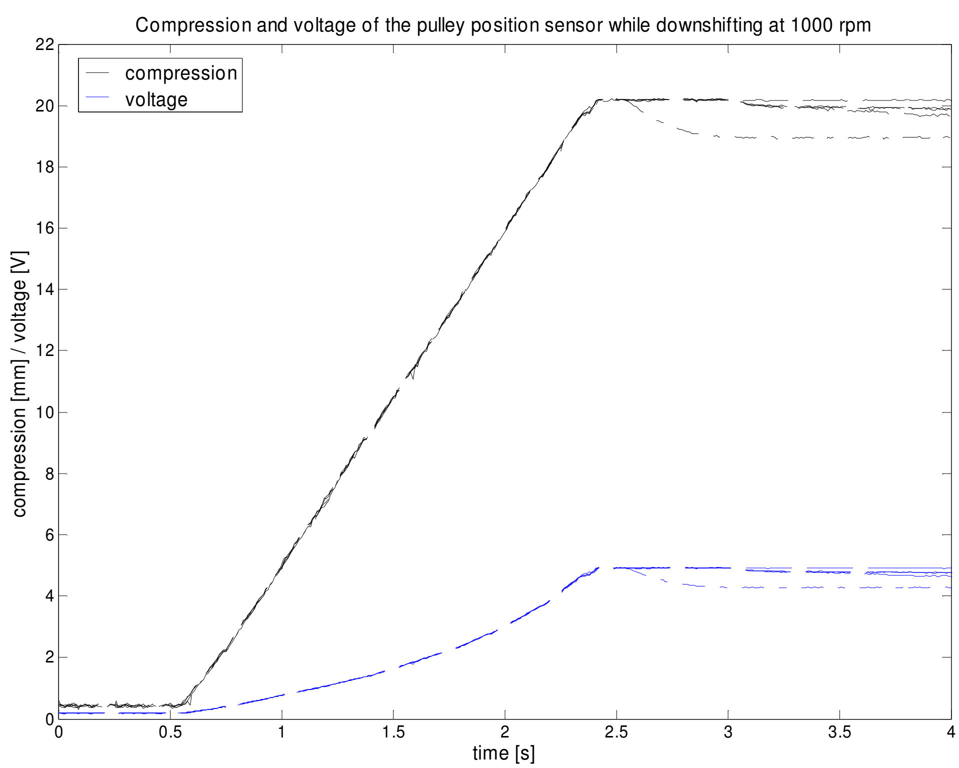


Figure 11.3: Compression and voltage of the PPS while the CVT shifts down at 1000 rpm

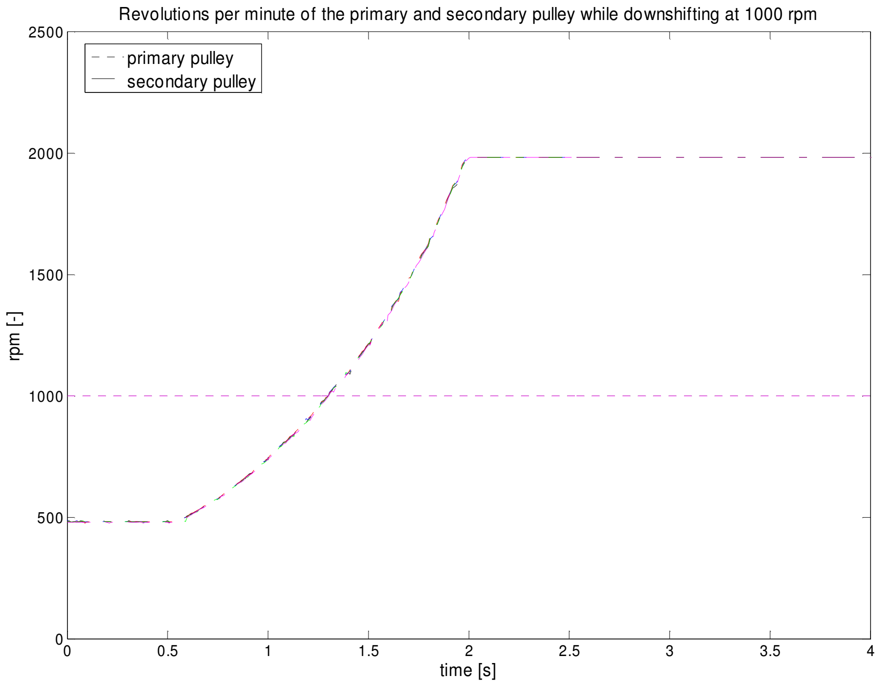


Figure 11.4: RPM of the primary and secondary pulley while the CVT shifts down at

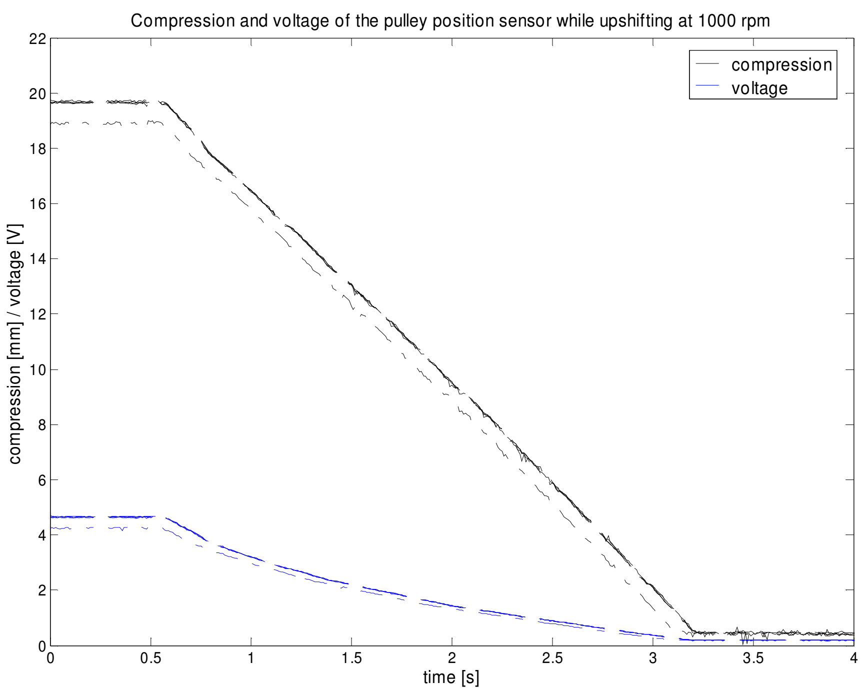


Figure 11.5: Compression and voltage of the PPS while the CVT shifts up at 1000 rpm

Note: In the final phase of down shifting of the CVT, the belt looses the contact with the pulley sheaves. The result of this is shown in figure 11.5 and 11.6. The lines of the measurements are not exactly the same.

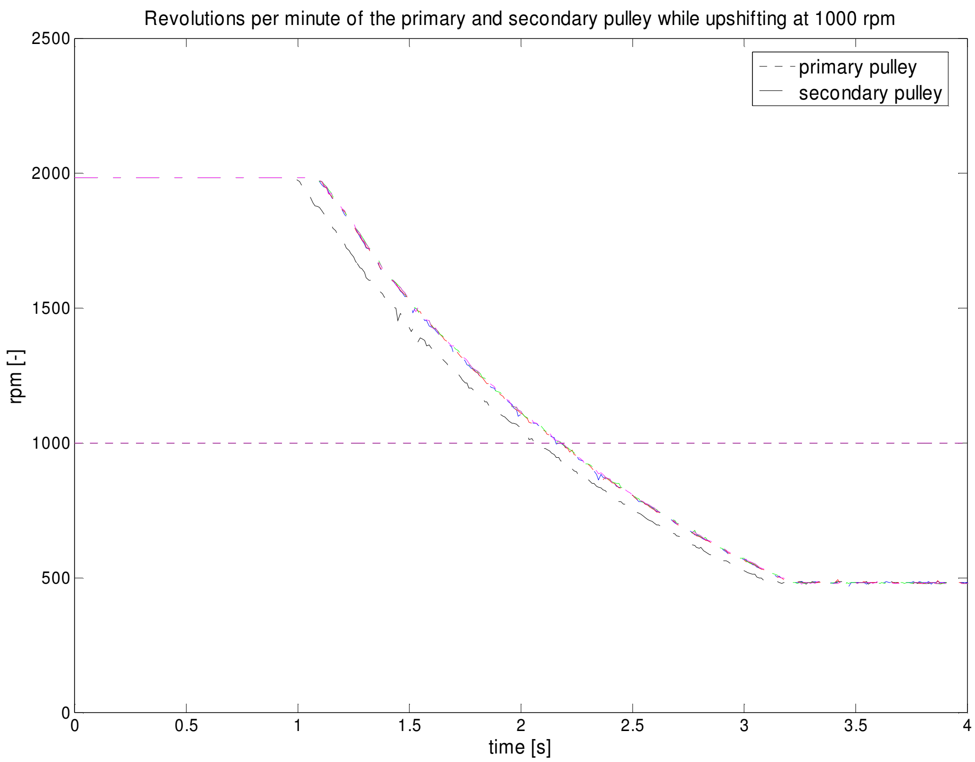


Figure 11.6: RPM of the primary and secondary pulley while the CVT shifts up at 1000 rpm

RPM primary pulley	Shift time [s]
1000 (down)	1.47
1000 (up)	2.14
2000 (down)	1.45
2000 (up)	1.93
3000 (down)	1.45
3000 (up)	1.86

Table 11.2: Shift times of the SECVT at different motor speeds

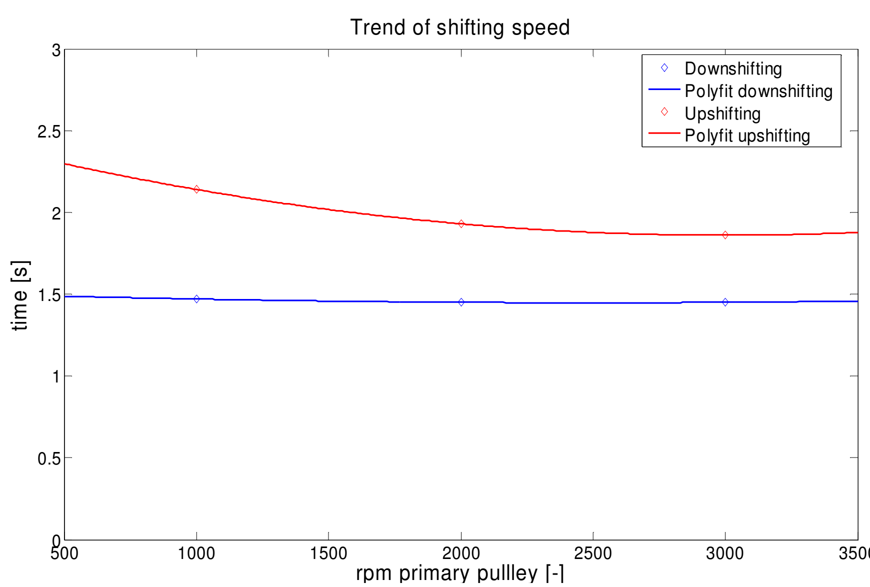


Figure 11.6: Shift speeds plotted for different rpm of the primary pulley

Chapter 12

Recommendations to achieve higher performance

In order to achieve even a higher performance of the CVT, some modifications could be made. This can improve the reliability and the performance of the race car. The following recommendations are suggestions. None of them are tested in reality.

CVT casing

The weight of the casing can be reduced. This can be achieved with modifying the original casing with milling or a design of a new casing of other material. A material such as carbon fiber can save approximately two third of the weight. With this material is a complex production method is required.
Since the CVT variator has a dry belt and mechatronic actuation, the casing does not need to be entirely closed, which means that holes can be drilled in non critical areas.

Pulley sheaves weight reduction

In order to reduce the overall weight and inertia of the pulley sheaves, the pulley sheaves can be modified. Part of the pulley sheaves can be removed (figure 12.1). Another option is to redesign the pulley sheaves of another material. With the use of lightweight aluminum a lot of weight can be saved. The aluminum can be treated with non-electrolyte Ni-P plating so that a good friction coefficient, abrasion and resistance can be achieved [www.coatingservice.nl]. A FEM analysis could prove the strength of the pulley sheaves, so no bending occurs.

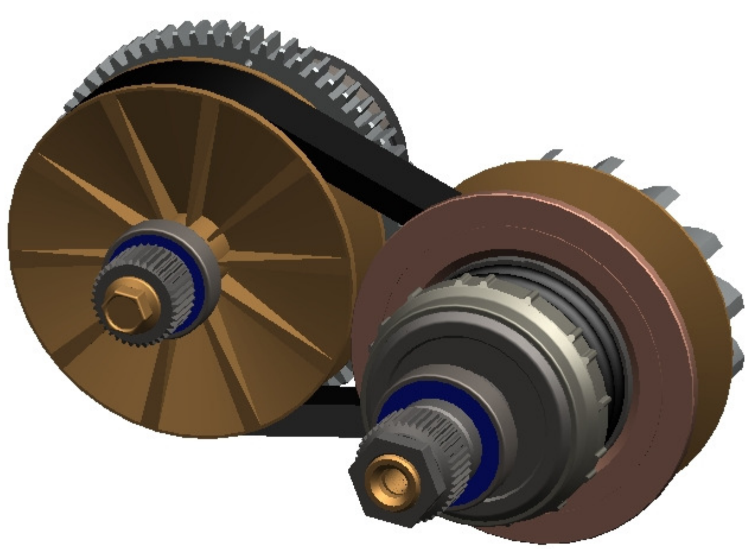


Figure 12.1: Concept for reducing the weight of the pulley sheaves

Cooling of the CVT

To ensure that the produced heat in the CVT can be transported to the environment, some modifications can be done. The air inlet in the CVT casing can be milled, to enlarge the area of the inlet. Another option is to install a fan with another shape on the secondary pulley, to achieve a higher airflow in the CVT casing. This modification should improve the reliability and wear of the belt.

Connection CVT with engine

To get a compact design and low center of gravity the original engine crankcase can be redesigned. The gearbox is not necessary any more, so the layout of the crankcase can be altered. This can save some weight of the crankcase and the center of gravity of the engine can be lowered. A complete new design of the crankcase can achieve these goals. For more information, see [*Modification of a Formula Student race car engine, for addition of a Continuously Variable Transmission*].

Chapter 13

Conclusion

In this bachelor final project the implementation of a Suzuki Electronically-controlled Continuously Variable Transmission is researched. First, the driveline of a Suzuki Burgman 650 is studied and an engine selection is made. An engine of a Suzuki GSX-R 600 is chosen.
The functioning of the SECVT is researched with a reversed engineering study. The primary pulley of the CVT is electro-mechanically actuated with a DC-motor, gear train and a spindle. The secondary pulley will follow the displacement of the primary pulley because of a spring that is incorporated in the design of the secondary pulley.
The belt of the CVT is a dry hybrid belt (Bando AVANCE). This belt has the good qualities of a metal and rubber belt combined in one design. Besides that the efficiency is higher than 90% when the primary torque is more than 20 Nm.
The combination of a Suzuki GSX-R 600 engine with a SECVT might give some problems. The forces on the belt are a lot higher in comparison to the Burgman 650 design. The manufacturer normally applies safety factors to their design. So the overloading of the CVT will probably not cause any problems. It might appear that there is more wear of the belt. In the design of a race car this will not be a problem, because of the shorter lifecycle of the parts.
The shift speed of the CVT is tested on a test bench at Drivetrain Innovations. The results of the measurements were satisfying. The CVT can shift faster than the race car can accelerate or decelerate.
A judge of Formula Student England said: 'The concept of the implementation of a SECVT in a race car is ambitious. It is a lot of work but with a good team it is possible!'

University Racing Eindhoven participated in the Formula student competition in England (Silverstone) with there concept of the URE05. With this concept they won the first price for best design in class 3 and the first price for overall winner of class 3.

Figure 13.1: The class 3 team members of URE at the Silverstone circuit in England

Chapter 14

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Appendix A

Section of part of Burgman 650 drive line

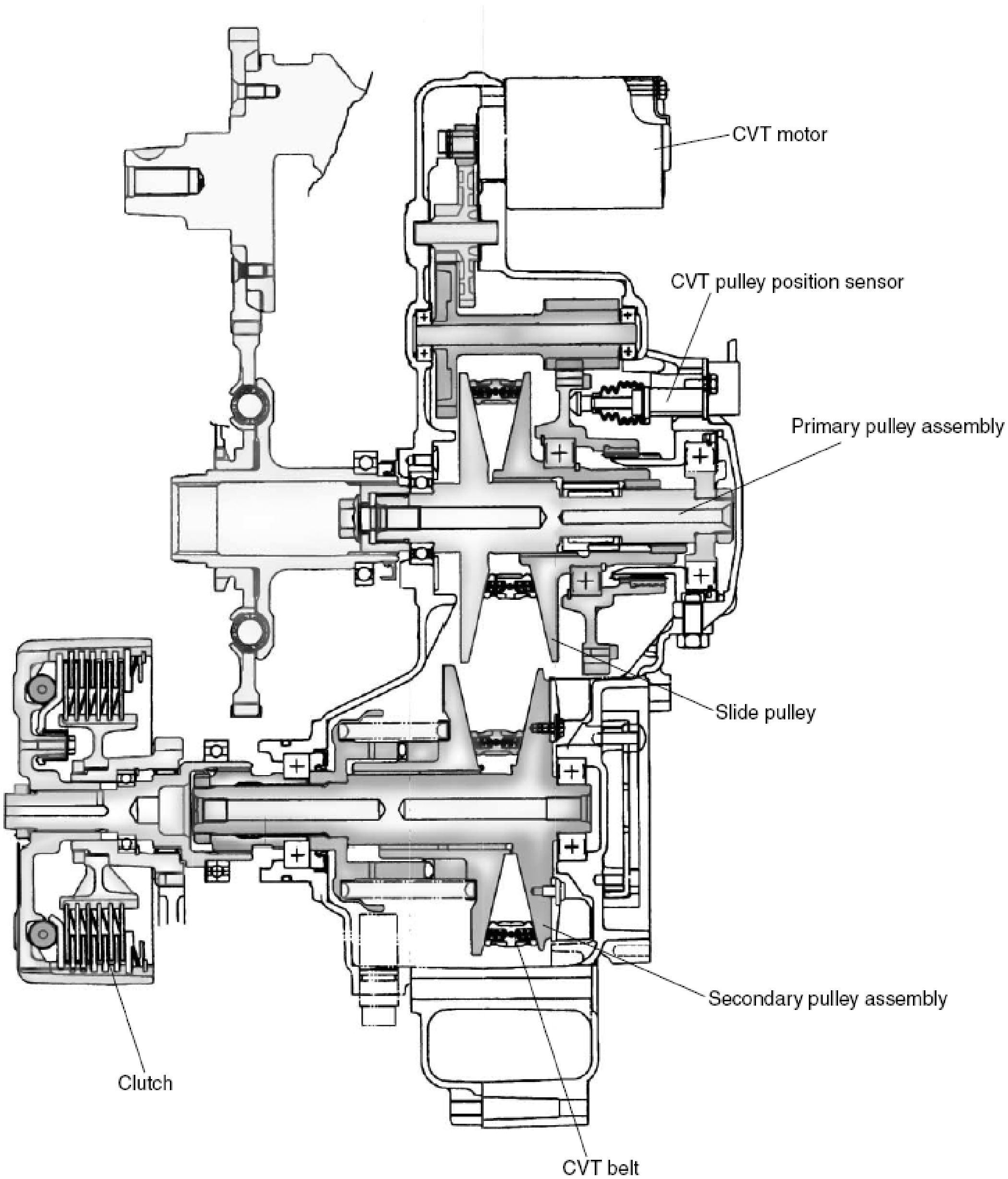


Figure A.1: Section of a Suzuki Burgman 650 driveline [Suzuki AN650 service manual]

Appendix B

M-file for calculation of power of modified Suzuki GSX-R 600 engine

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%% Power of modified Suzuki GSXR 600 engine %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Auteur: Berry Kuijpers

clc
clear all
close all

%%%%%%%%%% determination of constants %%%%%%%%%%

efficiency_drivetrain = 0.92; % assumption drivetrain of Suzuki GSX-R 600 is 92% efficient [-]



%%%%%%%%%% Measured values of modified Suzuki GSX-R 600 engine %%%%%%%%%%

P_measured
=[12;14.1;16.4;18.5;21.8;27.5;31.3;35;39;43.7;49.1;49;50.5;51.8;51.8;52.5;53;52.5;51.3;50;48;41]
; % Power of engine [kW]
rpm_crank =
[3000;3500;4000;4500;5000;5500;6000;6500;7000;7500;8000;8500;9000;9500;10000;10500;110
00;11500;12000;12500;13000;13500]; % Revolutions per minute of the engine [-]
w_crank = rpm_crank * (2*pi/60); % Angular velocity of the crank [rad/s]



%%%%%%%%%% Calculation of power of the engine ar crank %%%%%%%%%%%%%

P_crank = (1/efficiency_drivetrain)* P_measured; % Power of engine at crank [kW]
T_crank = (P_crank * 10^3) ./ w_crank; % Torque of engine at crank [Nm]


%%%%%%%%%% Figure %%%%%%%%%%%%

figure
plotyy(rpm_crank,P_crank,rpm_crank,T_crank)
axis([3000 13000 0 80]);
xlabel('RPM');
ylabel('Power [kW]');
title('Power of modified Suzuki GSX-R 600 engine at crank');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix C.1

Exploded view SECVT

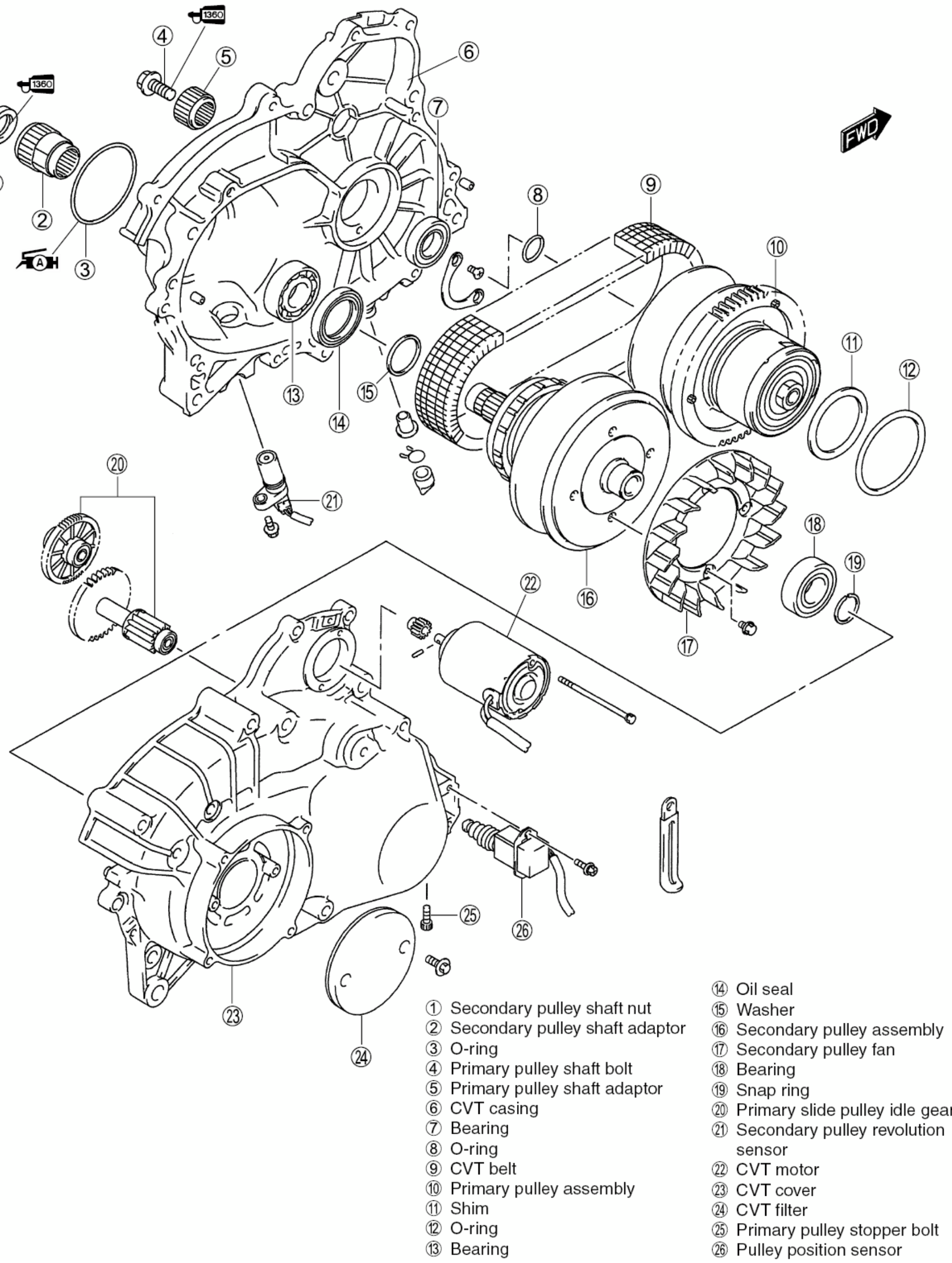


Figure C.1: Exploded view of SECVT [Suzuki AN650 service manual]

Appendix C.2

Exploded view primary pulley assembly SECVT

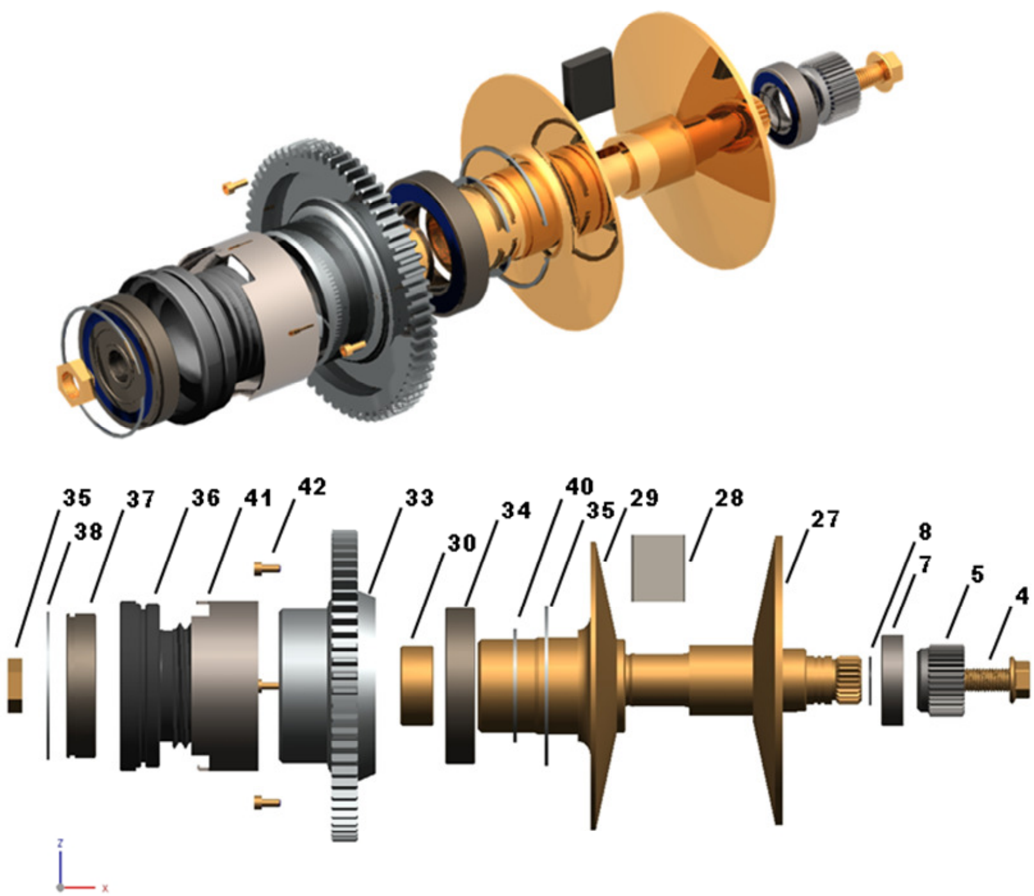


Figure C.2: Exploded view of primary pulley assembly

Primary pulley

4 Primary pulley shaft bolt
5 Primary pulley shaft adaptor
7 Bearing
8 O-ring
27 Primary fixed pulley
28 Key
29 Primary slide pulley
30 Plain bearing bush
33 Primary slide pulley gear
34 Bearing
35 Snap ring
36 Screw shaft
37 Bearing
38 Snap ring
39 Nut
40 Snap ring
41 Primary pulley cover
42 Bolt

Appendix C.3

Exploded view secondary pulley assembly SECVT

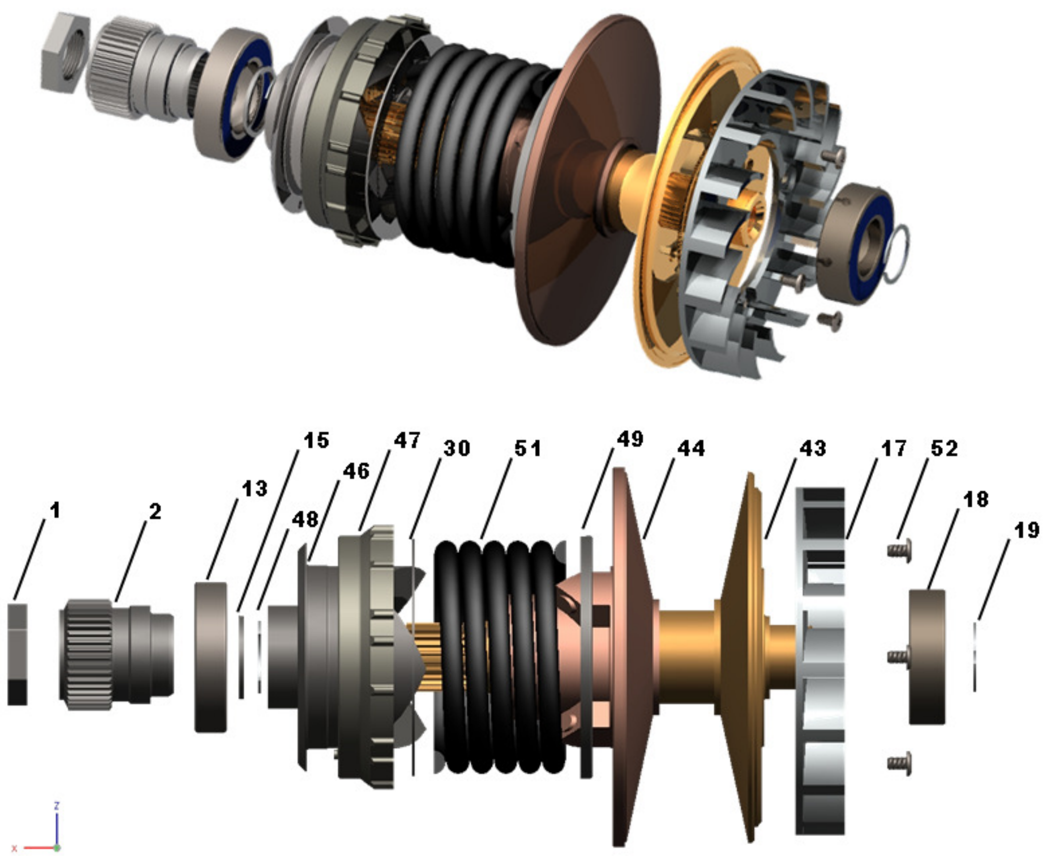


Figure C.3: Exploded view of the secondary pulley assembly

Secondary pulley

1	Secundary pulley shaft nut
2	Secundary pulley shaft adaptor
13	Bearing
15	Washer
17	Secondary pulley fan
18	Bearing
19	Snap ring
43	Secondary fixed pulley
44	Secondary slide pulley
46	Torque cam
47	Spring holder cap
48	Snap ring
49	Spring baseplate
50	Washer
51	Spring (compressed)
52	Bolt

Appendix C.4

Documentation of the SECVT

Nummer	Naam onderdeel	model UGS NX5.0	Materiaal	Gewicht (gram)	Aantal	Specificatie
1	Secundary pulley shaft nut	ja	Staal	20	1	Steek 34mm
2	Secundary pulley shaft adaptor	ja	Staal	135	1	
3	O-ring	nee	Rubber	< 5	1	72x2,5
4	Primary pulley shaft bolt	ja	Staal	30	1	M12x30
5	Primary pulley shaft adaptor	ja	Staal	110	1	
6	CVT casing	nee	Aluminium	1485	1	
7	Bearing	ja	Verschillend	50	1	Kogellager sealed NTN 6005LHA (25x47x12)
8	O-ring	ja	Rubber	< 5	1	25x1,2
9	CVT belt	ja	Verschillend	210	1	
10	Primary pulley assembly	ja				
11	Shim	ja	Staal	5	1	76x82x0,7
12	O-ring	ja	Rubber	< 5	1	87x3,5
13	Bearing	ja	Verschillend	75	1	Kogellager open Koyo 60/32C3 (32x58x13)
14	Oil seal	nee	Verschillend	5	1	
15	Washer	ja	Staal	< 5	1	27x32x2
16	Secondary pulley assembly	ja				
17	Secondary pulley fan	ja	Aluminium	105	1	
18	Bearing	ja	Verschillend	80	1	Kogellager sealed NTN 6205LHA (25x52x15)
19	Snap ring	ja	Staal	< 5		Circlip as 25mm
20	Primary slide pulley idle gear	ja	Verschillend	180	1	
21	Secondary pulley revolution sensor	nee	Verschillend	50	1	inductive pulse sensor
22	CVT motor	ja	Verschillend	695	1	
23	CVT cover	nee	Aluminium	2025	1	
24	CVT filter	nee	Verschillend	45	1	
25	Primary pulley stopper bolt	nee	Staal	10	1	M10x20
26	Pulley position sensor	nee	Verschillend	40	1	non-linear axial displacement sensor

Primary pulley assembly

7	Bearing	ja	Verschillend	50	1	Kogellager sealed NTN 6005LHA (25x47x12)
8	O-ring	ja	Rubber	< 5	1	25x1,2
27	Primary fixed pulley	ja	Staal	1260	1	
28	Key	ja	Staal		1	
29	Primary slide pulley	ja	Staal	1015	1	
30	Plain bearing bush	ja	Staal		1	
31	Plain bearing	nee	Verschillend		1	Glijlager (27x30x18)
32	Plain bearing	nee	Verschillend		1	Glijlager (36x40x30)
33	Primary slide pulley gear	ja	Aluminium	425	1	Z6 =64
34	Bearing	ja	Verschillend	170	1	Kogellager sealed NTN 6010LHA (50x80x16)
35	Snap ring	ja	Verenstaal	10	1	Circlip gat 80mm
36	Screw shaft	ja	Staal	505	1	Trapeziumdraad Tr64 x 14P4,67 LH
37	Bearing	ja	Verschillend		1	Kogellager seales NTN 6009LHA (**18**x75x16)
38	Snap ring	ja	Verenstaal		1	Circlip as 75mm
39	Nut	ja	Staal	10	1	Steek 24mm
40	Snap ring	ja	Verenstaal	5	1	Circlip as 50mm
41	Primary pulley cover	ja	Staal	55	1	
42	Bolt	ja	Staal	< 5	3	M4x10

	Secondary pulley assembly					
13	Bearing	ja	Verschillend	75	1	Kogellager open Koyo 60/32C3 (32x58x13)
15	Washer	ja	Staal	< 5	1	27x32x2
17	Secondary pulley fan	ja	Aluminium	105	1	
18	Bearing	ja	Verschillend	80	1	Kogellager sealed NTN 6205LHA (25x52x15)
19	Snap ring	ja	Verenstaal	< 5	1	Circlip as 25mm
43	Secondary fixed pulley	ja	Staal	1485	1	
44	Secondary slide pulley	ja	Staal	1045	1	
45	Plain bearing	nee	Verschillend		2	Glijlager (36x40x30)
46	Torque cam	ja	Staal	460	1	torque cam angle 32,5°
47	Spring holder cap	ja	Staal	40	1	18 notches
48	Snap ring	ja	Verenstaal	< 5	1	Circlip as 26mm
49	Spring baseplate	ja	Staal	20	1	
50	Washer	ja	Staal	10	1	72x90,7x0,8
51	Spring (compressed)	ja	Verenstaal	385	1	L_0 = 129 mm , k = 34,4 N/mm
52	Bolt	ja	Staal	< 5	4	M5x8
	Actuator					
21	Secondary pulley revolution sensor	nee	Verschillend	50	1	inductive pulse sensor
22	CVT motor	ja	Verschillend	695	1	
58	CVT motor shaft	ja	Staal		1	
59	CVT motor gear	ja	Kunststof		1	Z1 = 13
26	Pulley position sensor	nee	Verschillend	40	1	non-linear axial displacement sensor
33	Primary slide pulley gear	ja	Aluminium	425	1	Z6 = 64
53	Primary slide pulley idle gear 1	ja	Kunststof	20	1	Z2 = 58 , Z3 = 10
54	Primary slide pulley idle gear 1 shaft	ja	Staal	20	1	
55	Primary slide pulley idle gear 2	ja	Kunststof	50	1	Z4 = 35 , Z5 = 11
56	Primary slide pulley idle gear 2 shaft	ja	Staal	50	1	
57	Bearing	ja	Verschillend	10	4	Kogellager sealed NTN 6000LHA (10x26x8)

Appendix C.5

Specifications of the SECVT and Bando AVANCE belt

Specifications published by Aichi Machinery and Bando Chemical Industries

Avance belt (Bando Chemical Industries)		
Maximum torque	135	[Nm]
Material	Rubber/aluminum blocks	[-]
Width	25	[mm]
Length	612	[mm]
Pulley distance	148.5	[mm]
CVT Pulleys (Aichi Machine Industry Co.)		
Belt ratio (low)	1.980	[-]
Belt ratio (high)	0.460	[-]
Ratio change CVT	4.304	[-]
Pitch diameter primary pulley	Ø 65.8 – Ø 133.5	[mm]
Pitch diameter secondary pulley	Ø 130.3 – Ø 61.4	[mm]
Pulley outer diameter primary pulley	Ø 147	[mm]
Pulley outer diameter secondary pulley	Ø 143	[mm]
Efficiency (low) (input torque > 20 Nm)	$\eta_{CVT} > 95\%$	[-]

Table C.1: Specification of the SECVT and Bando AVANCE belt

Appendix D

Efficiency of the SECVT at different ratios

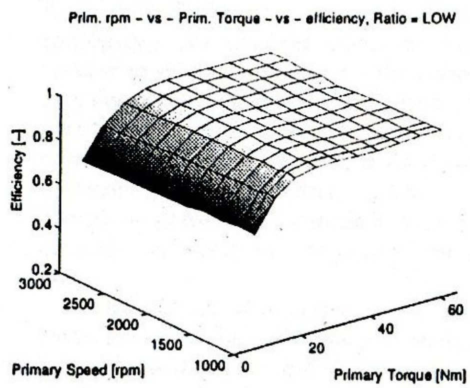


Figure D.1: The efficiency in ratio low

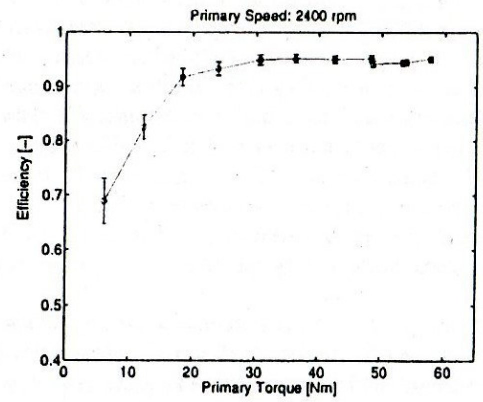


Figure D.2: Sample of the efficiency in ratio low

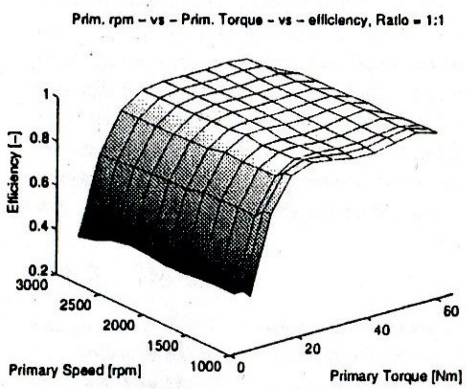


Figure D.3: The efficiency in ratio 1:1

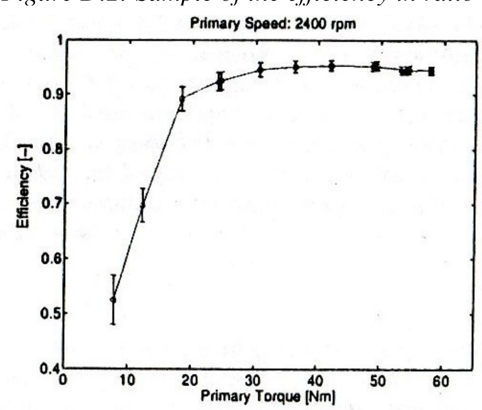


Figure D.4: Sample of the efficiency in ratio 1:1

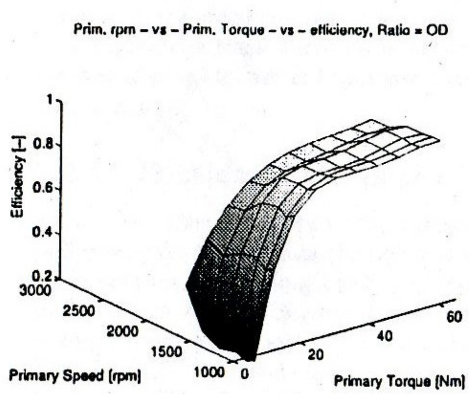


Figure D.5: The efficiency in ratio high

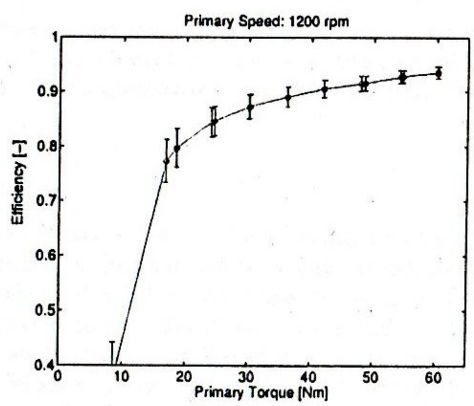


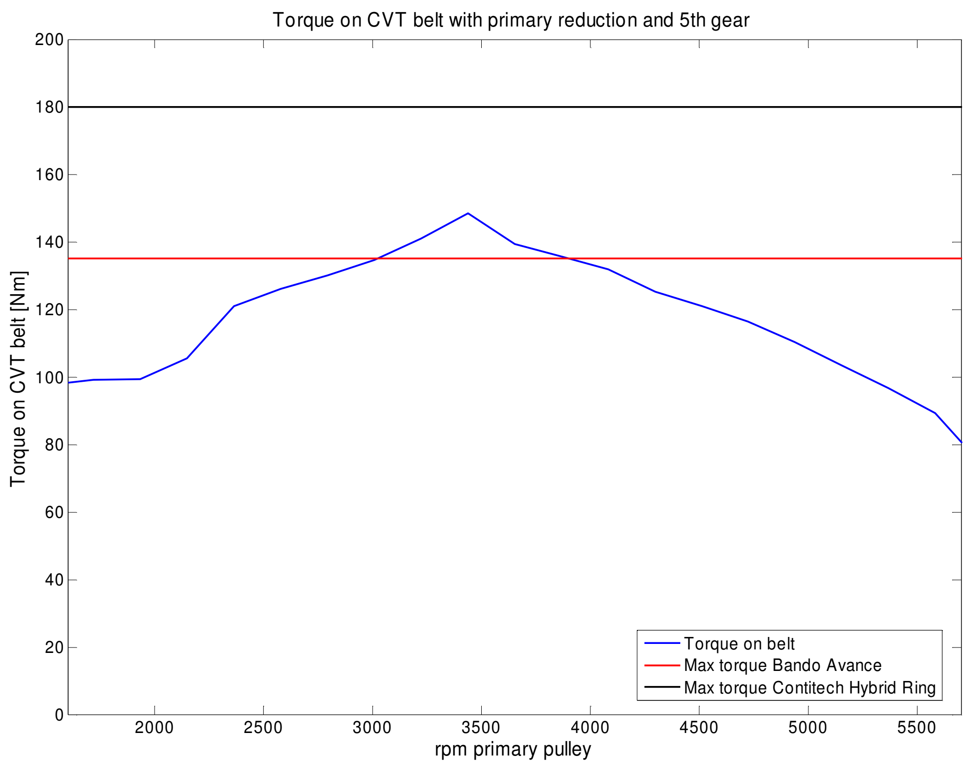
Figure D.6: Sample of the efficiency in ratio high

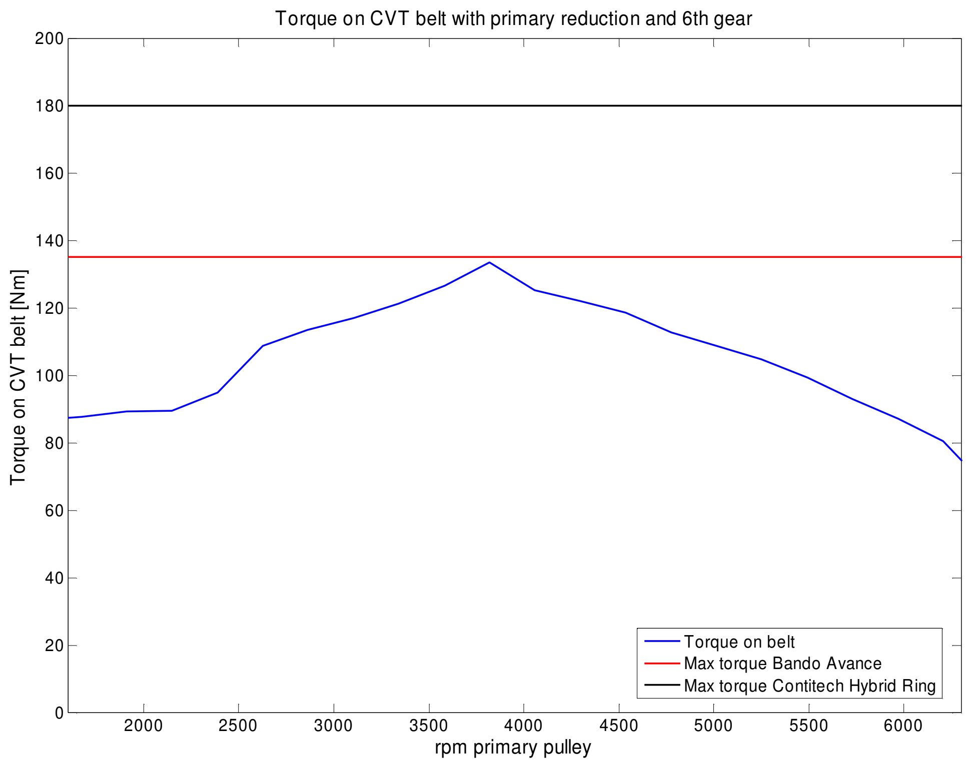
Remark: The plotted lines in figures D.2, D.4 and D.6 serve as a guide to the eye

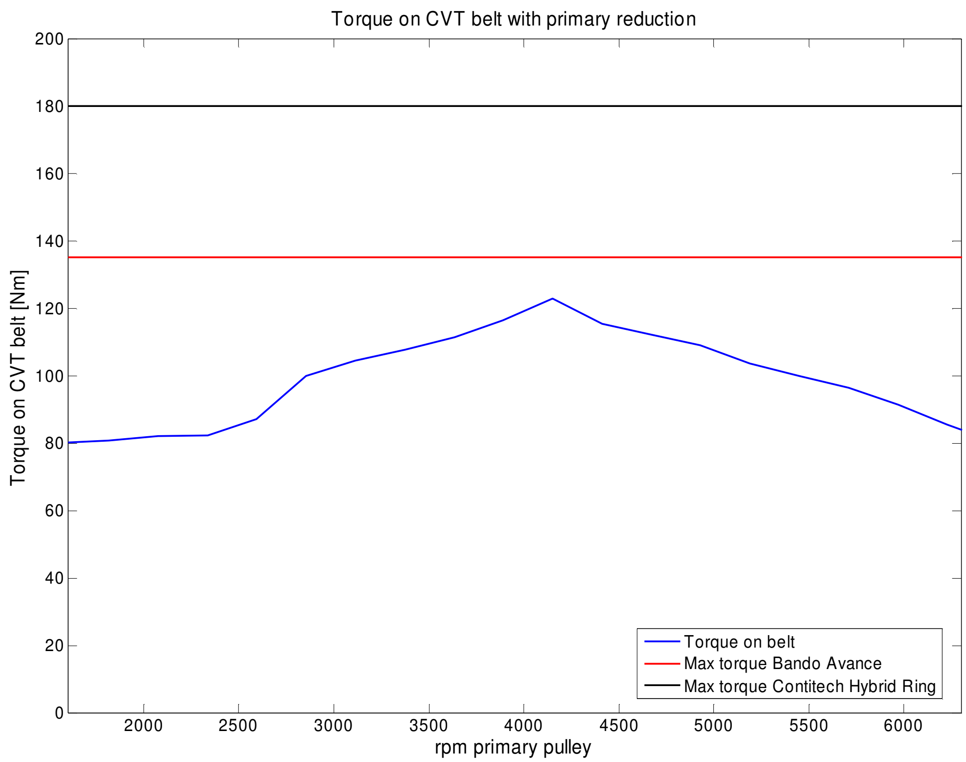
Appendix E.1

Torque on belt with different reductions

When the SECVT is connected to the Suzuki GSX-R 600 engine, a primary reduction is necessary to ensure a good lifetime of the belt. In the following figures different setups are shown. The setup with the primary reduction and fifth gear is the setup which is close to the ideal reduction. The M-file with the calculations of the forces on the belt is shown in appendix E.2.




Torque on CVT belt with primary reduction and 6th gear
Torque on CVT belt [Nm]
rpm primary pulley
Torque on belt
Max torque Bando Avance
Max torque Contitech Hybrid Ring


Torque on CVT belt with primary reduction
Torque on CVT belt [Nm]
rpm primary pulley
Torque on belt
Max torque Bando Avance
Max torque Contitech Hybrid Ring

Appendix E.2

M-file of the calculations of the forces on the CVT belt

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%% Determination of forces on the CVT belt %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Auteur: Berry Kuijpers

clc
clear all
close all

%%%%%%%%%% determination of constants %%%%%%%%%%

i_primair_gsx600 = 79/41; % Primary reduction Suzuki GSX-R 600 (out/in) [-]
gear_transmission_4 = 30/20; % Gear ratio of 4th gear (out/in) [-]
gear_transmission_5 = 29/24; % Gear ratio of 5th gear (out/in) [-]
gear_transmission_6 = 25/23; % Gear ratio of 6th gear (out/in) [-]
efficiency_drivetrain = 0.92; % assumption drivetrain of Suzuki GSX-R 600 is 92% efficient [-]
max_rpm_engine = 13000; % maximum revolutions per minute of the engine [-]
max_v_belt = 40; % maximum velocity of the CVT belt [m/s]
r_primary_pulley_min = 0.0329; % minimum pitch radius of primary pulley CVT [m]
r_primary_pulley_max = 0.06677; % maximum pitch radius of primary pulley CVT [m]
r_primary_pulley = [r_primary_pulley_min:0.0001:r_primary_pulley_max]'; % pitch radius on
primary pulley CVT [m]



%%%%%%%%%% Measured values of modified Suzuki GSX-R 600 engine %%%%%%%%%%

P_measured
=[12;14.1;16.4;18.5;21.8;27.5;31.3;35;39;43.7;49.1;49;50.5;51.8;51.8;52.5;53;52.5;51.3;50;48;41]
* 10^3; % Power of engine [W]
rpm_crank =
[3000;3500;4000;4500;5000;5500;6000;6500;7000;7500;8000;8500;9000;9500;10000;10500;110
00;11500;12000;12500;13000;13500]; % Revolutions per minute of the engine [-]
w_crank = rpm_crank * (2*pi/60); % Angular velocity of the crank [rad/s]



%%%%%%%%%% Calculation of power of the engine ar crank %%%%%%%%%%%%%%

P_crank = (1/efficiency_drivetrain)* P_measured; % Power of engine at crank [W]
T_crank = P_crank ./ w_crank; % Torque of engine at crank [Nm]
```

```
%%%%%%%%%% Calculation of ideal primary reduction %%%%%%%%%%%

max_w_engine = max_rpm_engine * ((2*pi)/60); % Maximum angular velocity of the engine [rad/s]
i_primair_perfect = max_w_engine / (max_v_belt / r_primary_pulley_max); % Ideal primary reduction ratio [-]


%%%%%%%%%% Calculation of variables %%%%%%%%%%%

% Primary reduction [-]
i_primair = [i_primair_gsx600
        i_primair_gsx600 * gear_transmission_5
        i_primair_gsx600 * gear_transmission_6
        i_primair_perfect];

% Angular velocity primary pulley CVT [rad/s]
w_cvt_primary_1 = w_crank / i_primair(1);
w_cvt_primary_2 = w_crank / i_primair(2);
w_cvt_primary_3 = w_crank / i_primair(3);
w_cvt_primary_4 = w_crank / i_primair(4);

% Revolutions per minute of primary pulley CVT [-]
rpm_cvt_primary_1 = w_cvt_primary_1 * (60/(2*pi));
rpm_cvt_primary_2 = w_cvt_primary_2 * (60/(2*pi));
rpm_cvt_primary_3 = w_cvt_primary_3 * (60/(2*pi));
rpm_cvt_primary_4 = w_cvt_primary_4 * (60/(2*pi));

% Torque on primary pulley CVT [Nm]
T_cvt_primary_1 = T_crank * i_primair(1);
T_cvt_primary_2 = T_crank * i_primair(2);
T_cvt_primary_3 = T_crank * i_primair(3);
T_cvt_primary_4 = T_crank * i_primair(4);

% Velocity of CVT belt on primary pulley CVT [m/s]
v_belt_1 = w_cvt_primary_1(21) * r_primary_pulley; %snelheid van de band (m/s)
v_belt_2 = w_cvt_primary_2(21) * r_primary_pulley;
v_belt_3 = w_cvt_primary_3(21) * r_primary_pulley;
v_belt_4 = w_cvt_primary_4(21) * r_primary_pulley;

Bando_Avance = 135 * ones(1,length(T_cvt_primary_1));
Contitech_Hybrid_Ring = 180 * ones(1,length(T_cvt_primary_1));
v_max = max_v_belt * ones(1,length(r_primary_pulley));
```

```
%%%%%%%%% Figures %%%%%%%%%%%

% Velocity of CVT belt on primary pulley CVT
figure
plot(r_primary_pulley,v_max,'r','LineWidth',2);
hold on
plot(r_primary_pulley,v_belt_1,'b','LineWidth',2);
plot(r_primary_pulley,v_belt_2,'g','LineWidth',2);
plot(r_primary_pulley,v_belt_3,'k','LineWidth',2);
plot(r_primary_pulley,v_belt_4,'m','LineWidth',2);
axis([r_primary_pulley_min r_primary_pulley_max 10 60]);
xlabel('radius primary pulley [m]');
ylabel('speed belt [m/s]');
title('Speed of the CVT belt @ 13000 RPM');
legend('max allowable speed','with primary reduction','with primary reduction and 5th gear','with
primary reduction and 6th gear','with ideal reduction');
hold off

% Torque on CVT belt with ideal primary reduction
figure
plot(rpm_cvt_primary_4,T_cvt_primary_4,'b','LineWidth',2);
hold on
plot(rpm_cvt_primary_4,Bando_Avance,'r','LineWidth',2);
plot(rpm_cvt_primary_4,Contitech_Hybrid_Ring,'k','LineWidth',2);
axis([1600 6300 0 200]);
xlabel('rpm primary pulley');
ylabel('Torque on CVT belt [Nm]');
title('Torque on CVT belt with ideal reduction');
legend('Torque on belt','Max torque Bando Avance','Max torque Contitech Hybrid Ring');
hold off

% Torque on CVT belt with original primary reduction Suzuki GSX-R 600 engine
figure
plot(rpm_cvt_primary_1,T_cvt_primary_1,'b','LineWidth',2);
hold on
plot(rpm_cvt_primary_1,Bando_Avance,'r','LineWidth',2);
plot(rpm_cvt_primary_1,Contitech_Hybrid_Ring,'k','LineWidth',2);
axis([1600 6300 0 200]);
xlabel('rpm primary pulley');
ylabel('Torque on CVT belt [Nm]');
title('Torque on CVT belt with primary reduction');
legend('Torque on belt','Max torque Bando Avance','Max torque Contitech Hybrid Ring');
hold off

% Torque on CVT belt with original primary reduction and 5th gear of Suzuki GSX-R 600 engine
figure
plot(rpm_cvt_primary_2,T_cvt_primary_2,'b','LineWidth',2);
hold on
plot(rpm_cvt_primary_2,Bando_Avance,'r','LineWidth',2);
plot(rpm_cvt_primary_2,Contitech_Hybrid_Ring,'k','LineWidth',2);
axis([1600 5700 0 200]);
xlabel('rpm primary pulley');
ylabel('Torque on CVT belt [Nm]');
title('Torque on CVT belt with primary reduction and 5th gear ');
legend('Torque on belt','Max torque Bando Avance','Max torque Contitech Hybrid Ring');
```

```
hold off

% Torque on CVT belt with original primary reduction and 6th gear of Suzuki GSX-R 600 engine
figure
plot(rpm_cvt_primary_3,T_cvt_primary_3,'b','LineWidth',2);
hold on
plot(rpm_cvt_primary_3,Bando_Avance,'r','LineWidth',2);
plot(rpm_cvt_primary_3,Contitech_Hybrid_Ring,'k','LineWidth',2);
axis([1600 6300 0 200]);
xlabel('rpm primary pulley');
ylabel('Torque on CVT belt [Nm]');
title('Torque on CVT belt with primary reduction and 6th gear');
legend('Torque on belt','Max torque Bando Avance','Max torque Contitech Hybrid Ring');
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix F.1

Thrust force calculations

The thrust force as is applied to the belt at the secondary pulley is displayed in figure 8.1. These values can be calculated using the following formulas. First the force applied by the spring is calculated (equation F.1). The second step is to calculate the force applied by the torque-cam mechanism (equation F.2). This force can not be lower than zero thus the outcome of equation F.2 has to be altered in case of $F_{cam} < 0$.
When combining F_{spring} and F_{cam}, the total thrust force F_{thrust} can be calculated using equation F.3.

$$F_{spring} = k_{spring} \cdot (x_0 + \Delta x_{spring}) \qquad \text{Equation F.1}$$

$$F_{cam} = \frac{\dfrac{T_{primair} \cdot \eta_{belt}}{2 \cdot r_{cvt}} - F_{spring} \cdot \mu_s \cdot R_{spring}}{R_{cam}} \qquad \text{Equation F.2}$$

$$F_{thrust} = \frac{F_{cam}}{\tan(\lambda + \alpha)} + F_{spring} \qquad \text{Equation F.3}$$

Variable	**Value [min/max]**
k_{spring}	34.4 N/mm (measured at Technoflex)
x_0	68.52 mm
Δx_{spring}	0 / 15.7 mm = 2 * R_{sec} * tan(β)
$T_{primair}$	0 / 149 Nm
η_{belt}	0.95 [-]
r_{cvt}	0.55 / 2.05 [-]
μ_s	0.12 [-]
R_{spring}	40.75 mm
R_{cam}	30.85 mm
λ	32.5°
α	$(\tan(\mu_c))^{-1}$
μ_c	0.18 [-]
β	13°

Table F.1 Values for calculation of thrust force [Study on the efficiency of an A-CVT : developments for the constant speed power take off , F.J.J. Gommans, 2003, Technische Universiteit Eindhoven]
** Variables are explained in M-file in appendix D??*

Appendix F.2

M-file for calculation of thrust force

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%% Calculation thrustforce SE-CVT with torquecam %%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Auteur: Berry Kuijpers

clc
clear all
close all

%%%%%%%%%% determination of constants %%%%%%%%%%

k_spring = 34400; % Spring rate of compression spring (measured at Technoflex) [N/m]
x_0 = 0.06852; % Initial setting length of spring [m]
efficiency_belt = 0.95; % Efficiency of the CVT belt [-]
r_cvt = [0.55:0.01:2.05]'; % Ratio coverage of SECVT [-]
delta_x_spring = [0:(0.0157/length(r_cvt)):0.0157]'; % Change of spring length [m]
mu_s = 0.12; % Coefficient of friction on spring seat [-]
R_spring = 0.04075; % Radius of spring (m)
R_cam = 0.03085; % Radius of torquecam (m)
labda = 32.5; % Cam angle [degrees]
mu_c = 0.18; % Coefficient of friction on cam [-]
alpha = atand(mu_c); % Friction angle on cam [degrees]
max_T_engine = 65.67; % Maximum torque of modified Suzuki GSX-R 600 engine [Nm]
i_primair_perfect = 2.2724; % Ideal primary reduction ratio of modified Suzuki GSX-R 600 engine
with SECVT [-]
max_T_engine_primair = max_T_engine * i_primair_perfect; % Torque of modified Suzuki GSX-R
600 engine at input shaft SECVT [Nm]
max_T_Burgman = 74; % Maximum torque of Suzuki Burgman 650 at imput shaft SECVT [Nm]
T_primair =[0 20 40 max_T_Burgman max_T_engine_primair]; % Torque at input shaft of SECVT
[Nm]



%%%%%%%%%%% Calculation of thrust force %%%%%%%%%%

figure % Open figure

for k = 1 : length(T_primair)

   for n = 1 : length(r_cvt)

      F_spring(n) = k_spring * (x_0 + delta_x_spring(n)); % Spring force [N]

      F_cam(n) = (((T_primair(k) * efficiency_belt)/(2 * r_cvt(n))) - (F_spring(n) * mu_s * R_spring))
/ R_cam; % Tangential force on cam [N]
```

```
        % In the case the tangential force on cam is below zero the output is altered
        if F_cam(n) < 0
            F_cam(n) = 0;
        end

        F_thrust(n) = (F_cam(n) / (tand(labda + alpha))) + F_spring(n); % Thrust force generated by
cam and spring [N]
    end

    plot(r_cvt,F_thrust,'b','LineWidth',2); % Plot outcome in figure
    hold on
end



%%%%%%%%%%% Figure properties %%%%%%%%%%%%%%%%%%%

axis([0.55 2.05 0 7000]); % Define axis properties
xlabel('CVT ratio [-]');
ylabel('Thrustforce [N]');
title('Thrustforce secondary pulley SE-CVT with torque cam');
legend('0 Nm','20 Nm','40 Nm','74 Nm','149 Nm');
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix G.1

Manufacturing drawing of adapter for test bench

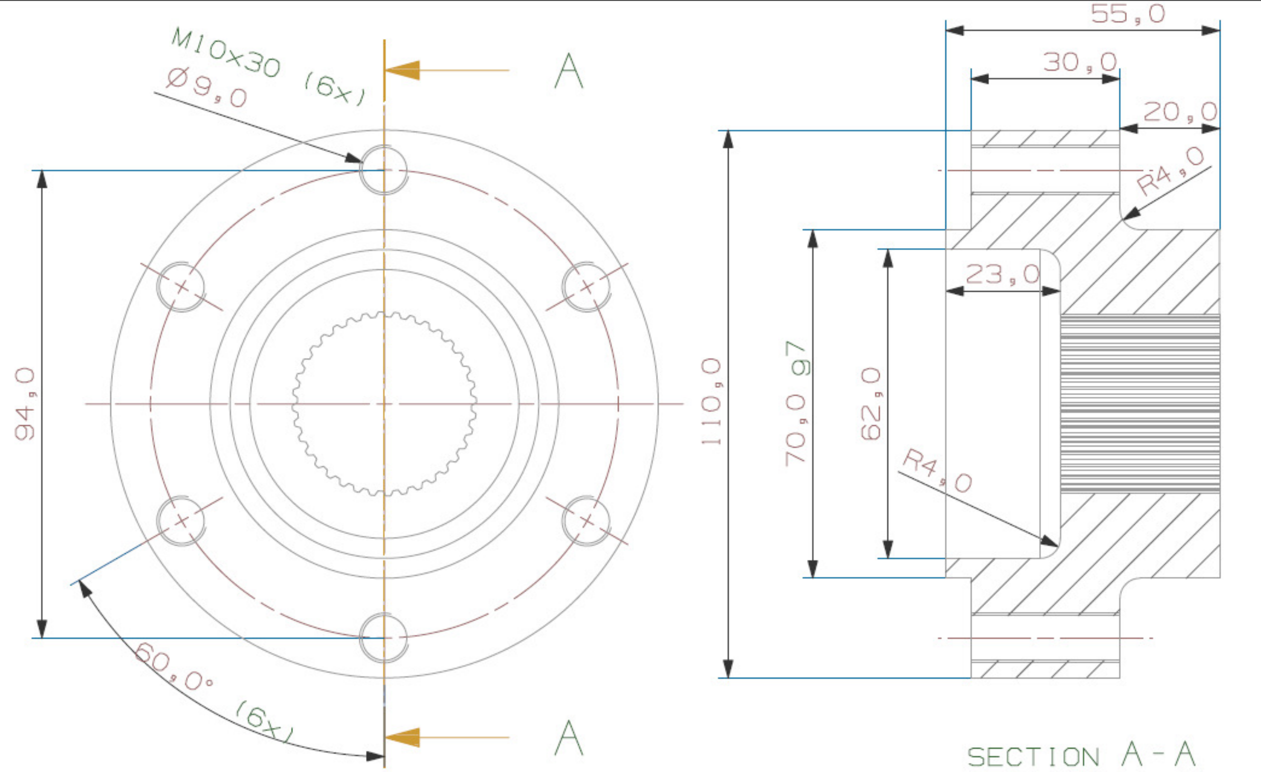


Figure M.1: Manufacturing drawing of adapter for test bench, manufactured at VDL

Appendix G.2

Wiring scheme of the test set up

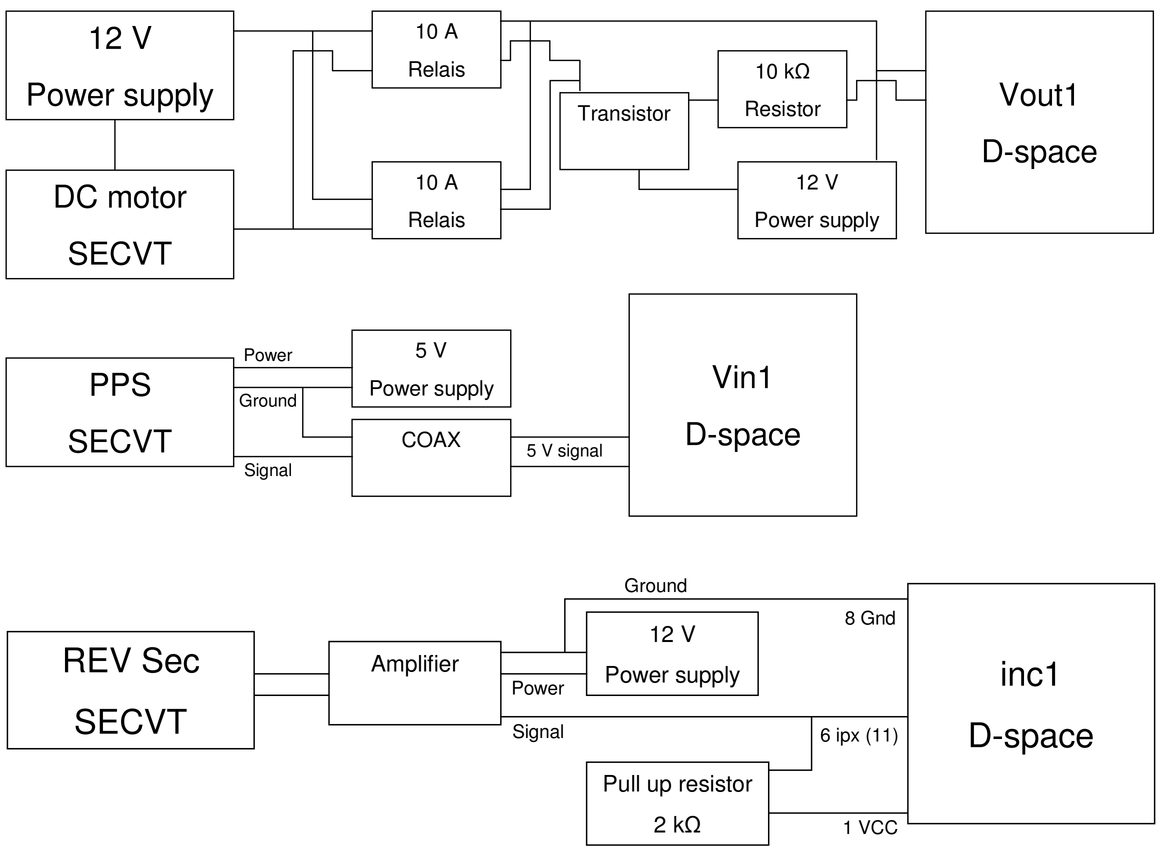


Figure N.1: Wiring scheme of the test set up at DTI

Appendix G.3

M-file for calibration of the pulley position sensor

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%% Pulley Position Sensor Calibration file %%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Auteur: Harrie Smetsers

%This file has been used to calibrate the pulley position sensor. A micro
%meter is taken and the sensor is compressed and every millimiter the
%output voltage is recorded. This measurement has been done 3 times and an
%average is taken.

clc
clear all
close all

%Measured data

pps_sensor = [0.1420 0.2340 0.3563 0.4847 0.6277 0.7650 0.9017 1.0500 1.1933 1.3433 1.5367
1.7467 1.9700 2.1900 2.4333 2.7233 3.0400 3.3967 3.8033 4.3000 4.8200;
            0     1     2     3     4     5     6     7     8     9     10     11     12     13     14     15     16
17     18     19     20];

%Polyfit

p1 = pps_sensor;
n= 4;
p2=polyfit(p1(1,:),p1(2,:),n);
x = 0:0.01:5; f = p2(1)*x.^4 + p2(2)*x.^3 + p2(3)*x.^2 + p2(4)*x + p2(5)

%Figure

figure(1);
   orient tall
   plot(p1(1,:),p1(2,:),'k--');
   hold on;
   plot(x,f,'r');
   ylabel('position [mm]');
   xlabel('voltage [V]');
   x1 = line(xlim,[3 3]);
   x2 = line(xlim,[18 18]);
   set(x1,'LineWidth',1,'LineStyle','-.','Color','k')
   set(x2,'LineWidth',1,'LineStyle','-.','Color','k')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix G.4

M-file for data processing of the measurement data while downshifting at 1000 rpm

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%% File to plot figures with the different measuring data %%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%% Auteurs: Harrie Smetsers and Berry Kuijpers

clear all
close all
clc

%%%% determination of constants %%%%

r_primary_max = 66.75;          %Maximum pitch radius primary pulley CVT [mm]
r_primary_min = 32.90;          %Minimum pitch radius primary pulley CVT [mm]
r_secondary_max = 65.15;        %Maximum pitch radius secondary pulley CVT [mm]
r_secondary_min = 30.70;        %Minimum pitch radius secondary pulley CVT [mm]
beta = 13;                      %Angle of pulley sheave with vertical [degrees]


%%%% polyline for converting pps sensor voltage to position %%%%

pps = [0.1420 0.2340 0.3563 0.4847 0.6277 0.7650 0.9017 1.0500 1.1933 1.3433 1.5367 1.7467
1.9700 2.1900 2.4333 2.7233 3.0400 3.3967 3.8033 4.3000 4.8200;
    0    1    2    3    4    5    6    7    8    9    10    11    12    13    14    15    16    17
18    19    20];
n= 4;
pps_fit=polyfit(pps(1,:),pps(2,:),n);


%%%% Load data measurements downshift with primary pulley at 1000 rpm %%%%

%%%% Measurement 1 %%%%
%Load data
load 1000rpmup_down_shift\test1000rpm1down.mat
t1  = trace_x;                  %time
V1  = trace_y(1,:);             %trigger signal of the shift motor
p1  = trace_y(2,:);             %pulley position sensor [mm]
P1  = trace_y(3,:);             %pulley position sensor [V]

% calculation rpm primary and secondary pulley
np1 = ones(1,length(t1)).*1000;                  %rpm primary pulley [-]
rprim1 = r_primary_max - (p1 ./ (2 * tand(beta)));  %radius primary pulley [mm]
for n = 1 : length(rprim1)
   if rprim1(n) < r_primary_min                 %correction for outer values
      rprim1(n) = r_primary_min;
```

```
    end
end
rsec1 = r_secondary_min + (p1 ./ (2 * tand(beta))); %radius secondary pulley [mm]
for n = 1 : length(rsec1)
    if rsec1(n) > r_secondary_max                %correction for outer values
        rsec1(n) = r_secondary_max;
    end
end
ns1 = np1 .* (rsec1./rprim1);                    %rpm secondary pulley [-]

% Trigger time signal
z1  = find(trace_y(1,:)>2.5);          %index for trigger signal on 0.5s
t1star = t1-t1(z1(1,1))+0.51;          %new time scale with trigger on 0.5s
t1 = t1star;                           %rewrite time


%%%% Measurement 2 %%%%
%Load data
load 1000rpmup_down_shift\test1000rpm2down.mat
t2  = trace_x;                         %time
V2  = trace_y(1,:);                    %trigger signal of the shift motor
p2  = trace_y(2,:);                    %pulley position sensor [mm]
P2  = trace_y(3,:);                    %pulley position sensor [V]

% calculation rpm primary and secondary pulley
np2 = ones(1,length(t2)).*1000;                  %rpm primary pulley [-]
rprim2 = r_primary_max - (p2 ./ (2 * tand(beta)));  %radius primary pulley [mm]
for n = 1 : length(rprim2)
    if rprim2(n) < r_primary_min                 %correction for outer values
       rprim2(n) = r_primary_min;
    end
end
rsec2 = r_secondary_min + (p2 ./ (2 * tand(beta))); %radius secondary pulley [mm]
for n = 1 : length(rsec2)
    if rsec2(n) > r_secondary_max                %correction for outer values
        rsec2(n) = r_secondary_max;
    end
end
ns2 = np2 .* (rsec2./rprim2);                    %rpm secondary pulley [-]

% Trigger time signal
z2  = find(trace_y(1,:)>2.5);          %index for trigger signal on 0.5s
t2star = t2-t2(z2(1,1))+0.51;          %new time scale with trigger on 0.5s
t2 = t2star;                           %rewrite time


%%%% Measurement 3 %%%%
%Load data
load 1000rpmup_down_shift\test1000rpm3down.mat
t3  = trace_x;                         %time
V3  = trace_y(1,:);                    %trigger signal of the shift motor
p3  = trace_y(2,:);                    %pulley position sensor [mm]
P3  = trace_y(3,:);                    %pulley position sensor [V]
```

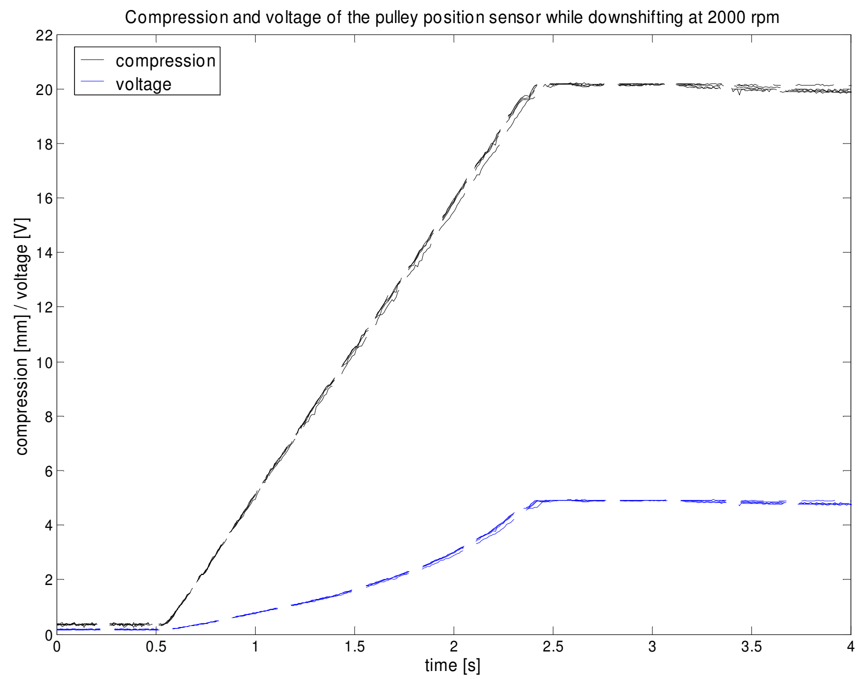
```
% calculation rpm primary and secondary pulley
np3 = ones(1,length(t3)).*1000;                    %rpm primary pulley [-]
rprim3 = r_primary_max - (p3 ./ (2 * tand(beta)));  %radius primary pulley [mm]
for n = 1 : length(rprim3)
    if rprim3(n) < r_primary_min                   %correction for outer values
        rprim3(n) = r_primary_min;
    end
end
rsec3 = r_secondary_min + (p3 ./ (2 * tand(beta))); %radius secondary pulley [mm]
for n = 1 : length(rsec3)
    if rsec3(n) > r_secondary_max                  %correction for outer values
        rsec3(n) = r_secondary_max;
    end
end
ns3 = np3 .* (rsec3./rprim3);                      %rpm secondary pulley [-]

% Trigger time signal
z3  = find(trace_y(1,:)>2.5);          %index for trigger signal on 0.5s
t3star = t3-t3(z3(1,1))+0.51;          %new time scale with trigger on 0.5s
t3 = t3star;                           %rewrite time


%%%% Measurement 4 %%%%
%Load data
load 1000rpmup_down_shift\test1000rpm4down.mat
t4  = trace_x;                         %time
V4  = trace_y(1,:);                    %trigger signal of the shift motor
p4  = trace_y(2,:);                    %pulley position sensor [mm]
P4  = trace_y(3,:);                    %pulley position sensor [V]

% calculation rpm primary and secondary pulley
np4 = ones(1,length(t1)).*1000;                    %rpm primary pulley [-]
rprim4 = r_primary_max - (p4 ./ (2 * tand(beta)));  %radius primary pulley [mm]
for n = 1 : length(rprim4)
    if rprim4(n) < r_primary_min                   %correction for outer values
        rprim4(n) = r_primary_min;
    end
end
rsec4 = r_secondary_min + (p4 ./ (2 * tand(beta))); %radius secondary pulley [mm]
for n = 1 : length(rsec4)
    if rsec4(n) > r_secondary_max                  %correction for outer values
        rsec4(n) = r_secondary_max;
    end
end
ns4 = np4 .* (rsec4./rprim4);                      %rpm secondary pulley [-]

% Trigger time signal
z4  = find(trace_y(1,:)>2.5);          %index for trigger signal on 0.5s
t4star = t4-t4(z4(1,1))+0.51;          %new time scale with trigger on 0.5s
t4 = t4star;                           %rewrite time


%%%% Measurement 5 %%%%
%Load data
```

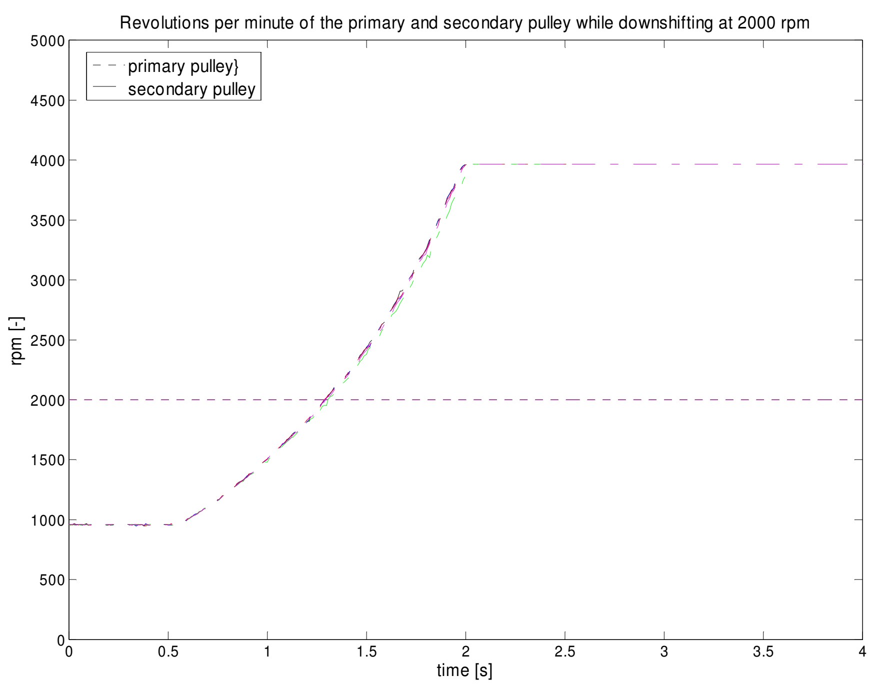
```
load 1000rpmup_down_shift\test1000rpm5down.mat
t5  = trace_x;                        %time
V5  = trace_y(1,:);                   %trigger signal of the shift motor
p5  = trace_y(2,:);                   %pulley position sensor [mm]
P5  = trace_y(3,:);                   %pulley position sensor [V]

% calculation rpm primary and secondary pulley
np5 = ones(1,length(t5)).*1000;                  %rpm primary pulley [-]
rprim5 = r_primary_max - (p5 ./ (2 * tand(beta)));  %radius primary pulley [mm]
for n = 1 : length(rprim5)
   if rprim5(n) < r_primary_min                 %correction for outer values
      rprim5(n) = r_primary_min;
   end
end
rsec5 = r_secondary_min + (p5 ./ (2 * tand(beta))); %radius secondary pulley [mm]
for n = 1 : length(rsec5)
   if rsec5(n) > r_secondary_max                %correction for outer values
       rsec5(n) = r_secondary_max;
   end
end
ns5 = np5 .* (rsec5./rprim5);                   %rpm secondary pulley [-]

% Trigger time signal
z5  = find(trace_y(1,:)>2.5);          %index for trigger signal on 0.5s
t5star = t5-t5(z5(1,1))+0.51;          %new time scale with trigger on 0.5s
t5 = t5star;                           %rewrite time


%%%% figures %%%%
% trigger signal
   figure(1);
   orient tall
   plot(t1,V1,'k--',t2,V2,'b--',t3,V3,'r--',t4,V4,'g--',t5,V5,'m--');
   axis([0 4 0 6])
   ylabel('voltage [V]');
   xlabel('time [s]');
   legend('m1','m2','m3','m4','m5')
   set(legend,'Location','NorthWest');

% rpm signal
   figure(2);
   orient tall
   plot(t1,np1,'k:',t1,ns1,'k-.');
   hold on
   plot(t2,np2,'b:',t2,ns2,'b-.');
   plot(t3,np3,'r:',t3,ns3,'r-.');
   plot(t4,np4,'g:',t4,ns4,'g-.');
   plot(t5,np5,'m:',t5,ns5,'m-.');
   axis([0 4 0 2500])
   ylabel('rpm [-]');
   xlabel('time [s]');
   legend('primary pulley','secondary pulley');
   title('Revolutions per minute of the primary and secondary pulley while downshifting at 1000
rpm');
   set(legend,'Location','NorthWest');
```

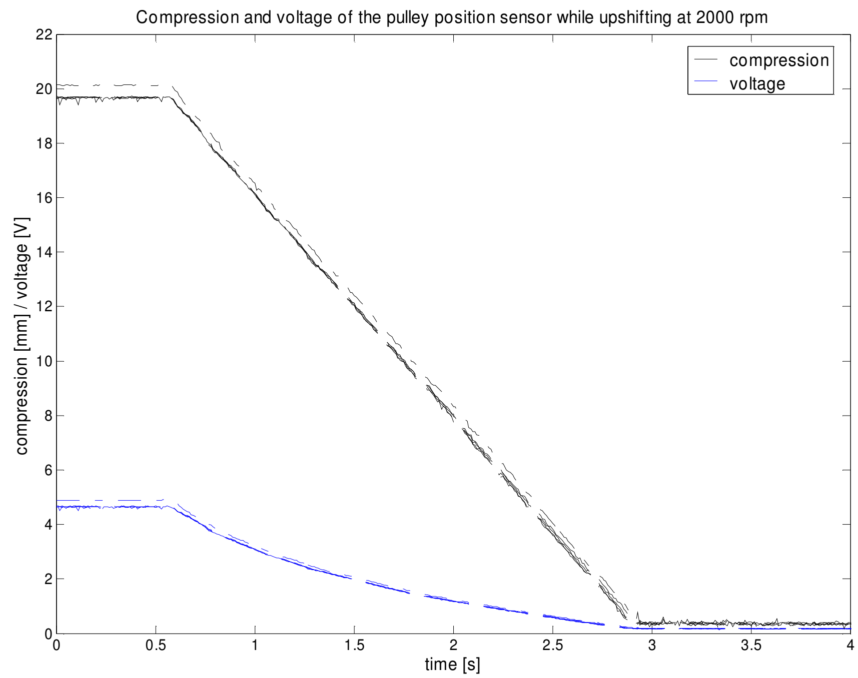
```
% ppsensor
   figure(3);
   orient tall
   plot(t1,p1,'k-.',t1,P1,'b-.'); hold on
   plot(t2,p2,'k--',t2,P2,'b--')
   plot(t3,p3,'k--',t3,P3,'b--')
   plot(t4,p4,'k--',t4,P4,'b--')
   plot(t5,p5,'k--',t5,P5,'b--')
   axis([0 4 0 22])
   ylabel('compression [mm] / voltage [V]');
   xlabel('time [s]');
   legend('compression','voltage');
   title('Compression and voltage of the pulley position sensor while downshifting at 1000 rpm');
   set(legend,'Location','NorthWest');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

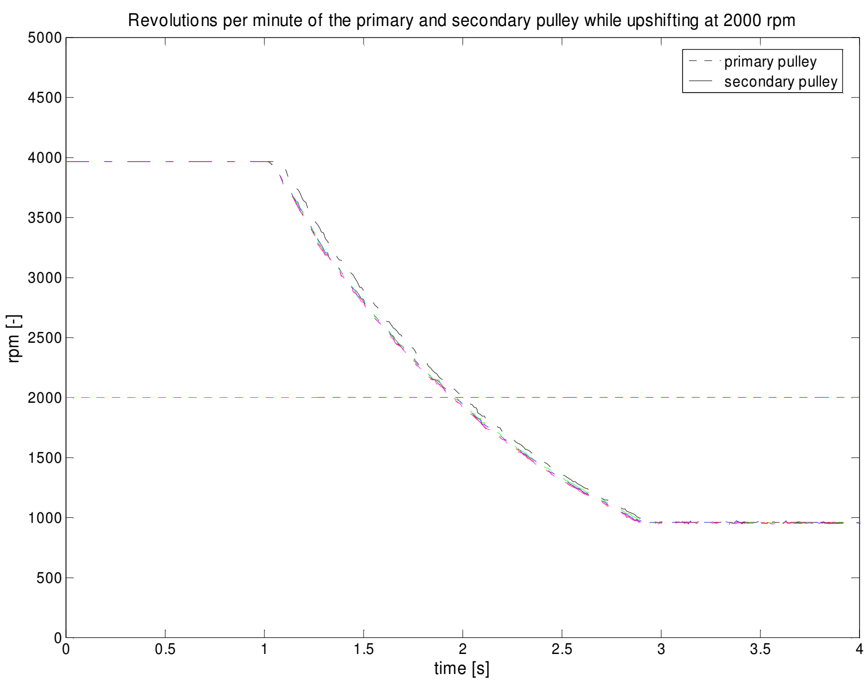
Appendix G.5

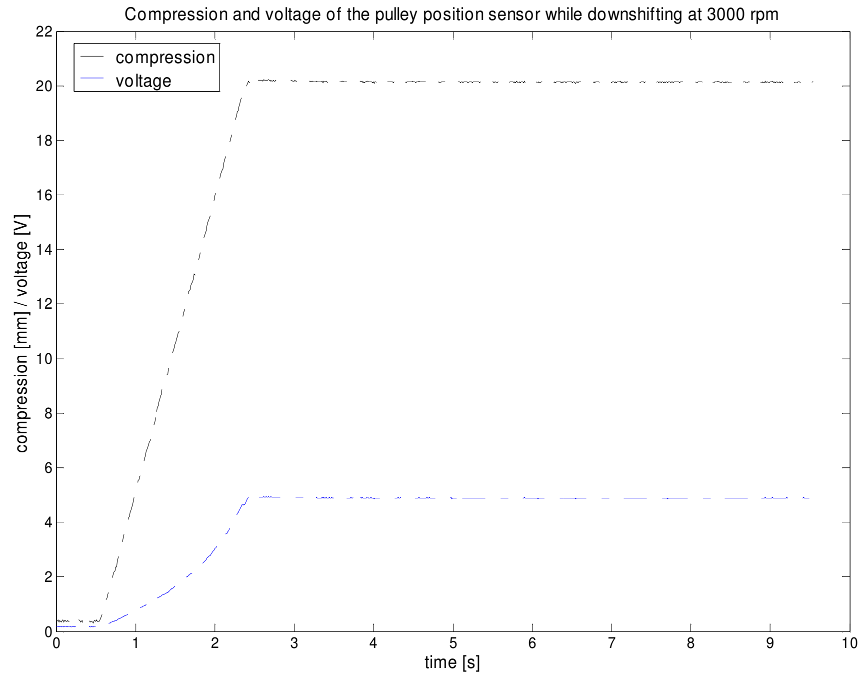
Test results of measurement shift speed at 2000 and 3000 rpm

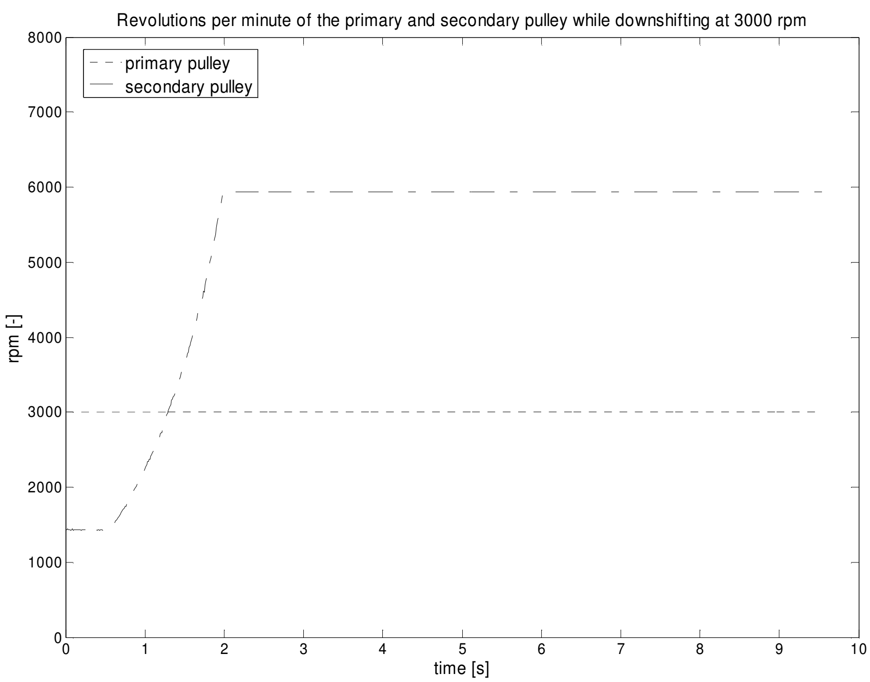


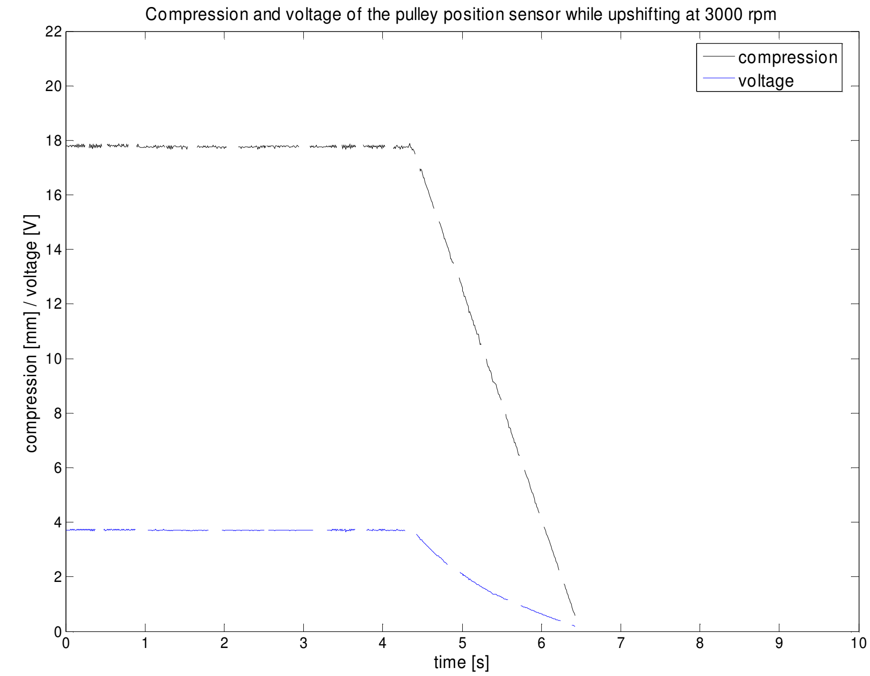


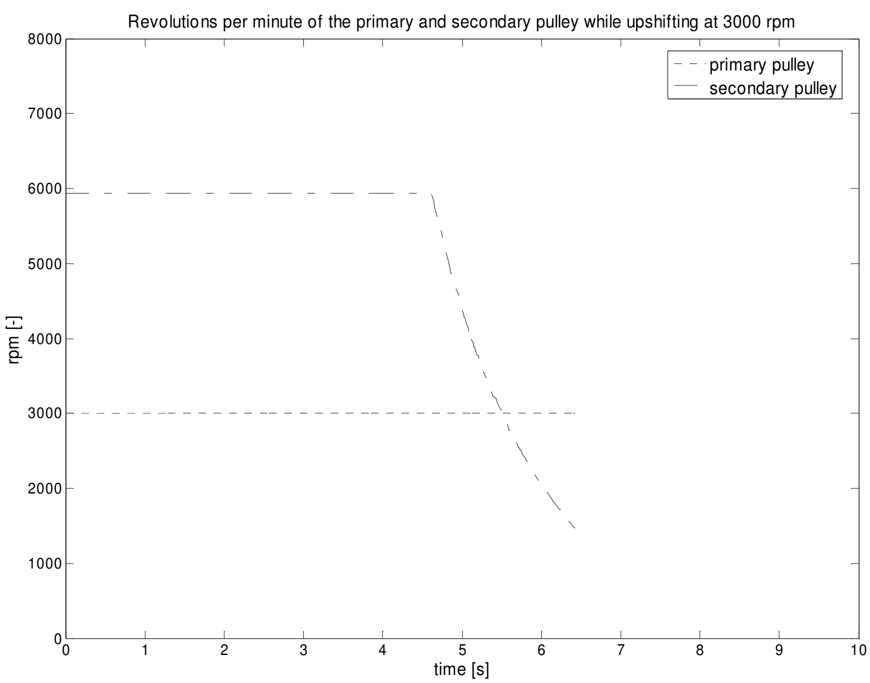

Compression and voltage of the pulley position sensor while upshifting at 2000 rpm
compression
voltage
compression [mm] / voltage [V]
time [s]


Revolutions per minute of the primary and secondary pulley while upshifting at 2000 rpm
primary pulley
secondary pulley
rpm [-]
time [s]


Compression and voltage of the pulley position sensor while downshifting at 3000 rpm
compression
voltage
compression [mm] / voltage [V]
time [s]
0
2
4
6
8
10
12
14
16
18
20
22
0
1
2
3
4
5
6
7
8
9
10


Revolutions per minute of the primary and secondary pulley while downshifting at 3000 rpm
primary pulley
secondary pulley
rpm [-]
time [s]
0
1000
2000
3000
4000
5000
6000
7000
8000
0
1
2
3
4
5
6
7
8
9
10


Compression and voltage of the pulley position sensor while upshifting at 3000 rpm
compression
voltage
compression [mm] / voltage [V]
time [s]
0
2
4
6
8
10
12
14
16
18
20
22
0
1
2
3
4
5
6
7
8
9
10


Revolutions per minute of the primary and secondary pulley while upshifting at 3000 rpm
primary pulley
secondary pulley
rpm [-]
time [s]
0
1000
2000
3000
4000
5000
6000
7000
8000
0
1
2
3
4
5
6
7
8
9
10