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Analysis of the CVT Efficiency by Simulation

All vehicle manufacturers desire an ideal vehicle that has the highest powertrain efficiency, best safety factor and ease of maintenance while being environmentally friendly. These highly valued vehicle development characteristics are only reachable after countless research hours. One major powertrain component to be studied in relation to these demands is the ***C****ontinuous* ***V****ariable* ***T****ransmission that a* ***H****ybrid* ***E****lectric* ***V****ehicle is equipped with. The CVT can increase the overall powertrain efficiency, offering a continuum variable gear ratios between established minimum and maximum limits. This paper aims to determine the losses of a CVT, operating on a HEV. Using simulation, the losses were computed and the fuel economy was analyzed. During various modes of operation, such as electric, regenerative braking, engine charge for maintaining the battery state of charge, the losses and their dependence with the control properties were analyzed. A relevant determination of precise losses is able to reduce them by using appropriate materials for their components and fluids, more efficient technical manufacturing and usage solutions and innovative control strategy.*

Keywords*: CVT, HEV, power loss, efficiency, simulation*

1. Introduction

New vehicles are equipped with various transmission types, the transmission being an important efficiency vehicle component. Environmental requirements and fuel economy demand an increase in the level of required improvements. Governmental regulations associated with customer expectations are setting important criteria to be followed by vehicle manufacturers for choosing the optimal transmission. The **C**ontinuously **V**ariable **T**ransmission is able to match the internal combustion engine operating requirements as an advantage of its continuous ratio range and to offer more comfort than other types of transmission. Used as important equipment on a Hybrid Electric Vehicle, the CVT has to deal with power expectance of the powertrain and to increase its efficiency.

Following significant research efforts, many researches admit that using the CVT is not an efficient way for an energy saving vehicle system. Many losses can be attributed to this system without taking into account the driver demands and the response of the engine to his demands. For a better fuel economy and less harmful emissions it is required that the engine operates close to the operating points. The easiest way to use this feature is to link the engine to a CVT. The CVT allows the engine to operate in a more fuel-efficient area compared with other transmissions. The CVT therefore plays a crucial role in the endeavors to improve the fuel economy.

2. Simulation of a virtual model

A hybrid electric vehicle model was built using AMESim. Having a post-transmission architecture (for a higher system efficiency, the electric motor-generator is linked behind the variator), a switched reluctance motor as the second propulsion source and a CVT, the model allows to investigate the harmful emissions, the fuel consumption and the powertrain efficiency.

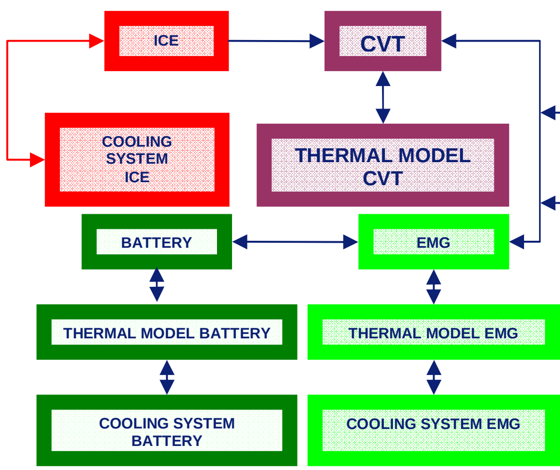


Figure 1. Model's architecture
(ICE=internal combustion engine, EMG=electric motor-generator, HCU=hybrid control unit)

CVT functional model

The CVT allows shifting (OR continuously varies) a range of ratios available between the low and overdrive ratios. The CVT is able to up-shift or down-shift moving the pulleys. From rest position, low ratio, when the drive pulley is smaller than the diameter of the driven pulley, to a higher ratio, the drive belt will transmit the torque and the power. Increasing the diameter of the drive pulley the ratio becomes higher, while the diameter of the driven pulley is decreasing. Both pulleys have one fixed and one mobile fledge. The primary and secondary mobile fledges are diagonally opposed. They are controlled electronically or hydraulically, in the second mode using the oil pressure from a pump. The pump can be independent and it is a high voltage oil pump.

In this model the CVT:

- uses efficiency table (based on temperature, primary pulley velocity and transmitted torque)
- clutch control and ratio from the HCU
- **NO** internal clutch
- thermal port is used just to compute thermal effects

The CVT is getting the engine torque in order to deliver it to the wheels. The clutch and the ratio are controlled by the hybrid control unit. For the relation with the thermal model it has a thermal port. The efficiency tables are set by the user as data files. The efficiency tables are developed using the primary rotary velocity and the output torque.

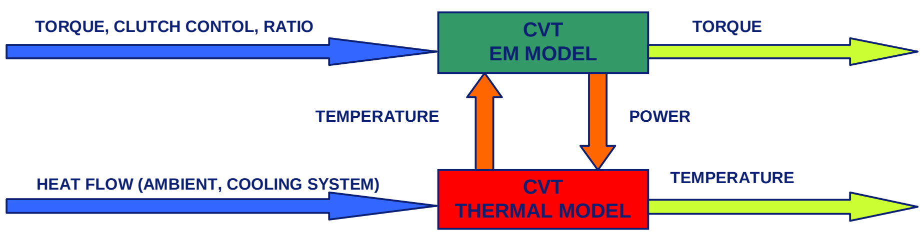


Figure 2. CVT functional model

For the input data, only some features were considered, namely some mechanical, geometrical and thermal properties from different parts of the CVT were taken into account, others were predefined in the software.

3. The main efficiency influences. Losses distribution

Building a simulation model that contains losses examination is a means to investigate the effects of metal-metal and metal-oil friction characteristics, in addition to the thermal transfer effects, on the efficiency of the CVT.

In the CVT, the losses can be presented/highlighted as follows:

A – losses from/inside main/various CVT's components;

B – losses between CVT's components

C – losses from internal oil

The components that will be detail investigated regarding the losses are:

a.1. variator

a.2. pump

a.3. the hydraulic circuit

a.4. reverse clutch

a.5. planetary gear set

a.6. drive clutch

Friction is the main heat generator inside the CVT, the losses being seen as friction losses and modeled as heat capacities and resistances (as explained in figure 5):

b.1. as a result of slipping between the belt and the pulley

b.2. as a result of slipping between the bands of the belt

b.3. as a result of slipping between the bands and the segments

b.4. as the drive torque transferred by compressive force between the belt segments

b.5. as bearing friction

b.6. belt torque losses as resistance to radial sliding when the belt segments are wedged into and out of the pulleys *not taking* into account the elasto-hydrodynamic lubrication between the segments and the pulleys, segment to pulley contact

Due to different operating modes, the behavior of the powertrain changes. For example, significant forces and torques will stress the CVT using the "only electric" mode or "conventional" mode. In the "hybrid" mode, the most important factor is the control of all the components involved into the vehicle operation.

4. Mathematically iterating the losses

Building a simulation model that contains losses aims to investigate the effects of metal-metal friction characteristics on the efficiency of the CVT belt. Using mathematically iterations, the simulation model will be easier to build.

Belt

The components of the belt and the geometry of the belt are very important to determine the mathematical relationships used to analyze their behavior in different circumstances:

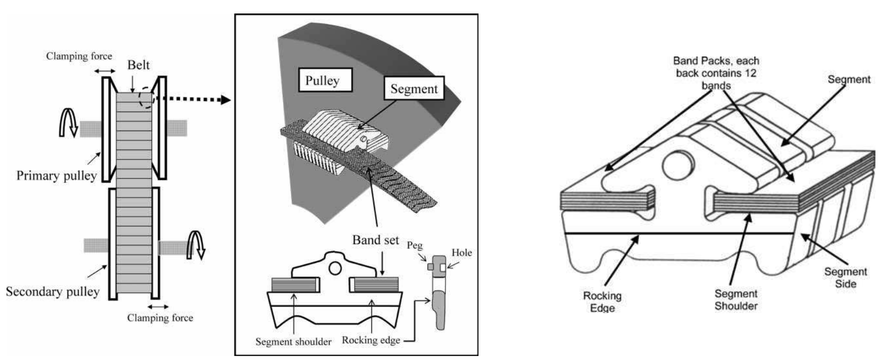


Figure 3. The components of a metal V-belt [7,3]

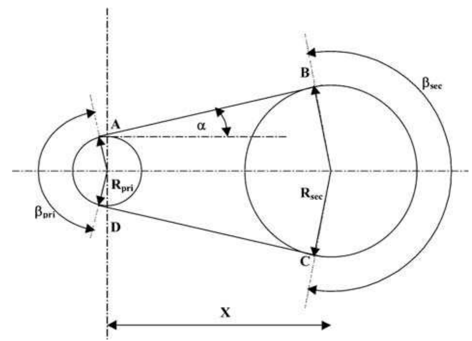


Figure 4. Belt geometry [3]

Regarding the belt losses, they can be mathematically modeled as friction losses caused by the slipping behavior between the belt segments and pulley, the segments and band, and between the bands. These mathematical models do not refer to the transmission efficiency of CVT under realistic running condition such as an overdrive speed ratio. The investigated belt consists of about 400 segments and 12 thin bands. Belt losses are influenced by friction that generates heat. Under steady state, the belt loss can be quantified using the following equation:

$$P_{belt} = \rho \cdot C_p \cdot V_{lfbelt} \cdot (T_{out} - T_{in}) \tag{1}$$

where ρ is the density of oil, C_p specific heat at contact pressure, L=V_{lfbelt} belt lubricant volumetric flowrate, T_{in} belt lubricant inlet temperature, T_{out} the splash temperature from the primary pulley.

Friction losses between the belt segment side and the pulley surface are based on realtive slipping and contact load:

$$P_{sp} = 2 \cdot \mu_{sp} \cdot F_{sp} \cdot V_{sp} \tag{2}$$

where μ_{sp} is the friction coefficient, F_{sp} the normal load, V_{sp} the realtive slipping speed for the **s**ide-**p**ulley interface.

To determine the friction coefficient the torque capacity of the tested oil (M_{max}) and the radius to the rocking edge on the primary pulley can be used:

Eroare! Obiectele nu se creează din editarea codurilor de câmp.

(3)

where λ is the half pulley angle, F_{ax} axial clamping force on a pulley , R_p radius to the rocking edge on the primary pulley.

Friction losses between segment shoulder and innermost band are:

$$P_{sb} = \mu_{sb} \cdot N_{sb-a} \cdot V_{sb-a} + \mu_{sb} \cdot N_{sb-st} \cdot V_{sb-st} \tag{4}$$

where μ is the friction coefficient, N is the normal load and sb-a refers to the segment shoulder/innermost band interfaces in the arc part, while sb-st in the straight part of the belt.

Friction losses between the bands, for 12 sheets of thin metal are:

$$P_{bb} = \mu_{bb} \cdot \sum_{n=2}^{12} \left[N_{bb-a}(n) \cdot V_{bb-a}(n) \right] + \mu_{bb} \cdot \sum_{n=2}^{12} \left[N_{bb-st}(n) \cdot V_{bb-st}(n) \right] \quad (5)$$

Total losses for the belt can be expressed as follows:

$$P_{belt} = P_{sp} + P_{sb} + P_{bb}\,, \quad (6)$$

The belt losses can be computed if the input / output torques and rotary velocities are available through measurements.

The torque loss depends of the clamping pressure (P_s), pulley ratio (i_p), primary pulley rotary velocity (n_{p1}) and torque input. Reducing the clamping force, it allows reducing the losses (using the measurements):

$$F_{clamp} = \frac{\left[\left(S_{f.abs} - 1 \right) \cdot T_{\max} + T_{pri} \right] \cdot \cos(\lambda)}{2 \cdot r_{pri} \cdot \mu} = \frac{S_{f.rel} \cdot T_{pri} \cdot \cos(\lambda)}{2 \cdot r_{pri} \cdot \mu} \quad (7)$$

where T_{pri} is the primary torque, λ the pulley angle, r_{pri} the primary pulley radius, μ friction coefficient between the belt and the pulley, $S_{f.abs}$=1.3 absolute safety factor, $S_{f.rel}$=1 relative safety factor[13] for the clamping force.

Oil pump

In this model, the oil pump is a high voltage oil pump. The driving torque and the rotating speed perform the oil pump operation. The oil pump losses are caused by the required pressure to push the oil out and to move the pulleys' fledges. The oil pump has the same rotational speed as the engine, which is why the clamping force depends on the engine rotational speed. Therefore, the oil pump torque loss depends on pulley ratio and belt input torque.

The pump capacity is proportional with engine speed and pump's flow (Q_{pump}), and the consumed pump's torque (T_{pump}) depends of the pressure drop (Δp), capacity (V_{th}) and hydro-dynamical efficiency (η_{hm}) of the pump.

$$T_{pump} = \frac{\Delta p_{pump} \cdot V_{th}}{2 \cdot \pi \cdot \eta_{hm}} \quad (8)$$

$$V_{th} = \left(\frac{Q_{pump}}{n_{pump} \cdot \eta_{vol}} \right)_{critical} \quad (9)$$

The priority for the hydraulic circuit is the variator over the lubricating pressure level used for lubrication and cooling, the main losses being related to the variator.

Pulleys

The CVT has two pulleys, each of them having a fixed fledge and a mobile fledge, diagonally placed. The moving fledge is being moved by the clamping force provided by the oil pump. The losses from the pulleys are related to the friction between the belt and the pulleys while the belt is getting up and down on the internal side of the pulley, the friction between the mobile pulleys and the shafts.

Both pulleys deform elastically. These losses can be detailed as pulley deflection losses, which contain pulley wedge losses and pulleys penetration losses.

Pulley wedge losses occur at the entry and exit of the pulley, due to deformation of the pulley:

$$P_{wedgeI(II)} = \frac{R_{I(II)} \cdot \tan(\varphi) \cdot V_{rI(II)} \cdot N_{I(II)} \cdot \mu_{I(II)}}{t_{seg} \cdot \omega_{in}} \qquad (10)$$
$$P_{wedge,total} = 2 \cdot \left(P_{wedgeI} + P_{wedgeII}\right)$$

where P_{wedge} is pulley wedge losses, R pulley radius, φ[deg] pulley exit/entrance wedge angle, V_r[m/s] relative velocity, N[N] normal force, μ[-] friction coefficient, t_{seg}[m] thickness of one segment, ω_{in}[rad/s] rotational speed, while I(II) refers to the primary or secondary pulley.

The pulleys' deformations generate a second loss, caused by the segments of the belt penetrating into the pulley wedge angle and being forced out of the pulley wedge angle:

$$P_{penI(II)} = \frac{Q_{penI(II)} \cdot V_{belt}}{t_{seg} \cdot \omega_{in}} \qquad (11)$$
$$P_{pen,total} = P_{penI} + P_{penII}$$

where P_{pen} is pulley penetration losses, Q_{pen}[W] the power consumed by sliding one segment in and out of the wedge angle by his depth, V_{belt}[m/s] belt absolute velocity.

Bearings

Bearings friction is an important part of total losses. To compute bearing loads in order to determine the friction, the forces, which act on the shaft being supported by the bearing, must be determined. These loads contain dead load, a load produced while working and dynamic load. These can be theoretically calculated using mathematical equations, but in many cases is very difficult. Keeping in mind that inside the CVT the bearings are met on different shafts, including belt shafts and gears shafts, the following equations can be used:

- belt shaft load

$$K_t = \frac{19{,}1 \cdot 10^6 \cdot H}{D_p \cdot n} \qquad (12)$$

$$K_r = f_b \cdot K_t \qquad (13)$$

- gears shaft load (parallel shafts)

$$K_s = K_t \cdot \frac{\tan\alpha}{\cos\beta} \qquad (14)$$

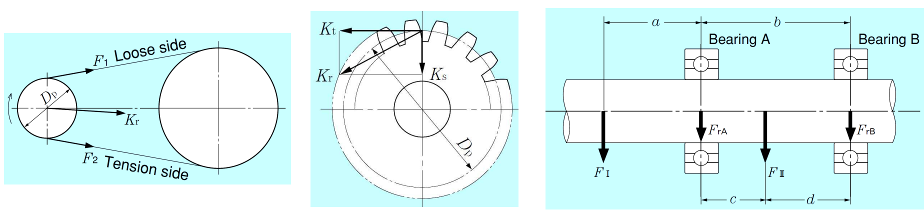
$$K_r = \sqrt{K_t^2 + K_s^2} \qquad (15)$$

where K_t[N] is the pulley/gear tangential load, H[kW] transmitted force, D_p[mm] pulley/gear pitch diameter, K_r[N] pulley radial load, f_b[-]=(1,5 – 2) V-belt factor, K_s[N] radial gear load, n[rot/min] rotational speed, α, β[deg] gear pressure/helix angle.

The bearing load distribution is also very important:

$$\begin{aligned} F_{rA} &= \frac{a+b}{b} \cdot F_I + \frac{d}{c+d} \cdot F_{II} \\ F_{rB} &= -\frac{a}{b} \cdot F_I + \frac{c}{c+d} \cdot F_{II} \end{aligned} \tag{16}$$

where F_{rA}[N] is the radial load on bearing A, F_{rB}[N] the radial load on bearing B, F_I[N] and F_{II}[N] radial loads on shaft



Belt loads *Gear loads* *Bearing load distribution*

Figure 5. Bearings loads [12]

5. Modeling the losses as heat transfer

Thermal effects

There are various numerical techniques to analyze the thermal behavior of the CVT. As the losses are evaluated as heat sources and heat effects, one way to model them is to associate geometrical shapes to each of the components, in order to determine their masses. To compute the heat sources and to describe the thermal effect inside the CVT, some assumptions were taken into account.

Temperature distribution was performed using conduction and convection. As specified before, the thermal masses and the thermal effects were computed as resistances. Knowing the losses distribution and the temperature distribution, a thermal network was built. These circuit elements represent the heat removal and transfer. The equivalent circuit was created with two principal assumptions:

- the temperature is assumed to be equal in all parts of the moving elements,
- the temperature of the outer components is consider to be equal.

Heat transfer:

- **conduction**
- from components to case/frame
- through shafts

- **convection**
- oil=thermal mass, oil flow=convective heat transfer

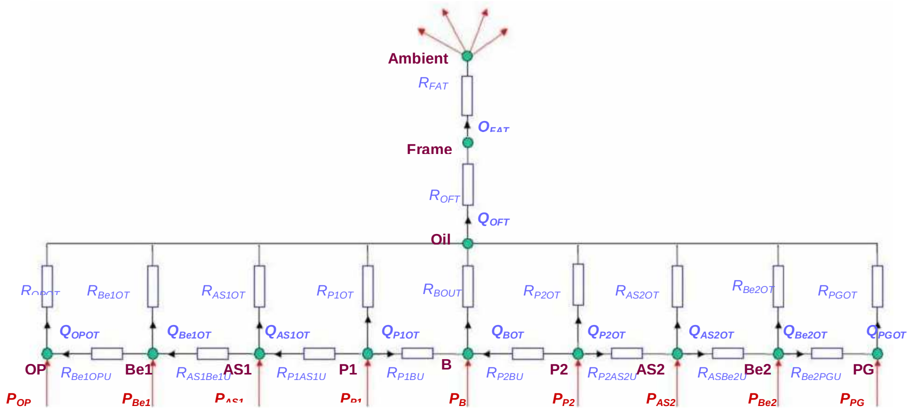


Figure 5. Thermal network

In the thermal network, the following notations were used: OP=oil pump, Be1/Be2=bearings from primary/secondary pulley, P1/P2=primary/secondary pulley, B=belt, AS1/AS2=axial shafts primary/secondary pulley, PG=planetary gear, T-convection, U-conduction, R-resistances. Each of the components was presented as thermal masses, with an illustration of the conduction or convection between them.

Cooling/heat dissipation

Due to the frictional losses between the belt and the pulleys' surfaces and between the belt internal contacts, the heat is being dissipated by variator operation. The fluid has a relevant cooling effect by its flow and its temperature. The fluid is moving through a separate radiator decreasing its temperature.

6. Results

Some results and graphs are able to be shown in order to validate the model. Taking into account that the simulation time is related to the New European Driving Cycle (NEDC) – 1180 seconds – all the dependencies were evaluated.

Simulation results

60-65% loss between belt and pulley
15-25% loss belt internal
10-20% loss bearings
95% CVT efficiency

The losses can be highlighted as: for the variator, between 48% and 37% - Over Drive, while 0% - Stand Still, for the pump from 17% to 12% - Over Drive, 13% - Stand Still, the hydraulic circuit near 4,7%, for the reverse clutch, near 2%, for the planetary gear set not more than 1%.

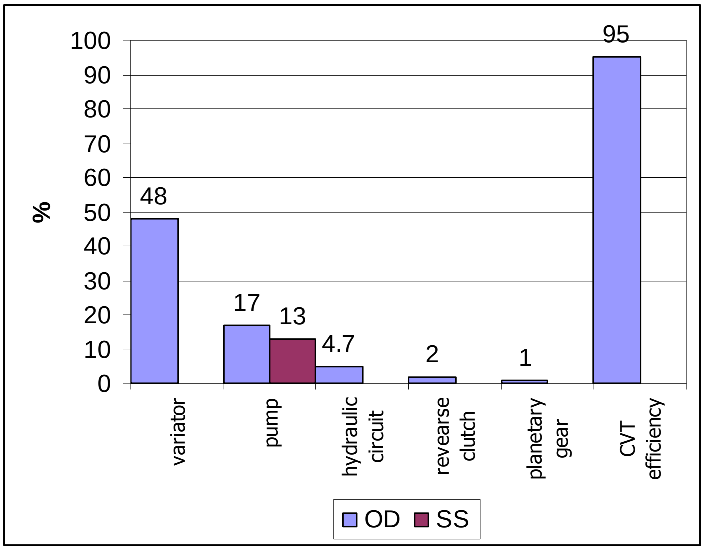


Figure 6. Losses evaluation

7. Conclusion

A detailed investigation and analysis has been performed into the functioning of the CVT. Creating this model allows to perform an energy analysis of the whole vehicle. Investigating the thermal effects the Hybrid Control Unit can be developed. The CVT efficiency can consequently be highlighted. After measuring the temperature in different points on the CVT, the created model is validated.

In order to reduce the power losses, allowances should be made for the following considerations:

- to reduce the slip losses and friction losses in the variator
- to reduce the required actuation power
- to improve balance between demanded and provided actuation power
- to generate actuation power in a more efficient way

The main step for reducing the variator losses is to reduce the clamping force by using a more developed control strategy. A new control is needed, using the slip between belt and pulley as the control parameter. To determine the slip it is straightforward to compare the geometrical ratio with the speed ratio of the variator. Having all of these available, the next step is to reduce the slip losses and friction losses in the variator.

The effect of speed on the pulley clamping force is more significant than the torque load effects.

The influence of the metal-metal friction characteristics on the transmittable torque capacity and the efficiency of the CVT have been determined.

The future research will contain evaluations that are more detailed.

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