

Innovative Self-optimising Clamping Force Strategy for the Pushbelt CVT

Erik van der Noll, Francis van der Sluis, Tom van Dongen and Arie van der Velde
Bosch - Van Doorne's Transmissie

Copyright © 2009 SAE International

ABSTRACT

The efficiency of continuously variable transmissions (CVT) based on the pushbelt principle is dominated by oil pump and variator losses that are directly related to the clamping force between the belt and pulleys. Currently applied safety strategies lead to relatively high forces that prevent destructive slip under all conditions. Recently, vehicle tests have shown that a large efficiency increase and significant fuel savings can be reached when the variator is operated close to the slip limit [1].

This paper describes the theory and realization of a self-optimizing control algorithm that is based on the transfer behavior of the variator in which slip and other effects play a role. The new algorithm does not need a given setpoint and so keeps the control simple and robust. It controls the clamping force to low values under both static and dynamic conditions without requiring additional or adapted hardware.

The new algorithm enables an accelerated introduction of new CVT controller technology to the market and will help the CVT to maintain its forefront position on fuel consumption.

INTRODUCTION

The latest introductions of automatic transmissions to the market show that the fuel consumption of vehicles with a manual transmission can be met and surpassed.

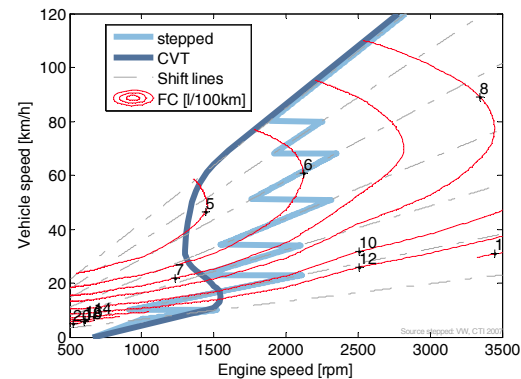


Fig. 1 Shift pattern of a CVT and stepped automatic and its relationship to fuel consumption (FC)

A closer look reveals that Continuously Variable Transmissions (CVT) based on the pushbelt principle are at the forefront. With fuel consumption currently being a main driver, this results in a rapid expansion of this technology. To sustain this growth, minor reductions in fuel consumption are no longer sufficient. Innovation is needed. This paper presents such an innovation.

The focus on fuel consumption translates into two important targets for transmission development. The first one is variability or the ability of the transmission to adapt its ratio towards the optimal point of driveline operation. The second one is transmission efficiency itself.

The limited variability of stepped transmission types like AT and DCT (**figure 1**), results in a fuel consumption disadvantage of about 10% when compared to CVTs [2]. An increase of the number of speeds only brings minor improvement at increased cost.

Regarding efficiency, some stepped concepts like AMT and dry DCT currently surpass continuously variable concepts in reaching the highest possible transmission efficiency. This enables them to close the gap on fuel consumption. But where the efficiency potential for these transmissions has virtually run out [3], the CVT shows large potential for further improvement [4].

By combining variability and efficiency, the CVT therefore has the potential to become the worlds leading transmission on fuel economy, a fact that has been recognized by most Japanese OEMs.

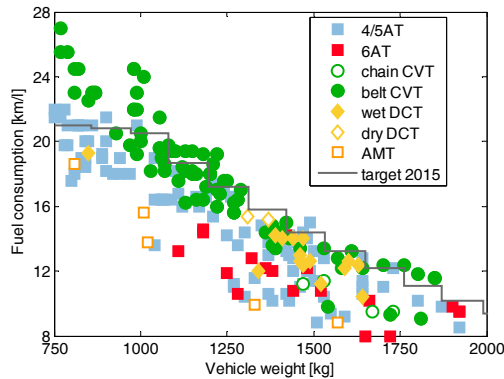


Fig. 2 Fuel consumption benchmark Japan (10-15 cycle), FWD gasoline applications. Source: OEM data

Figure 2 shows that the CVT on average outperforms all other transmission types in Japan. The Japanese cycles, with their relatively low maximum speeds enable the CVT its best performance. Due to the continuing improvement of CVT efficiency, also other global regions are in focus for the introduction of CVT on a larger scale [5].

In [1], the reduction of clamping forces by controlling the variator close to the slip limit, was identified as the major potential. Vehicle tests showed a reduction in fuel consumption between 5 and 5.5%. Initial research focused on a control method based on a set-point and measured value for slip. Despite positive results, it proved laborious to introduce this technology to the market. Furthermore, a full coverage of the relevant driving cycles proved to be difficult.

To overcome these issues, a new self-optimizing control algorithm was developed. Both theory and realisation are explained in this paper. First, the variator and the current clamping force control method are discussed. Next, a closer look is taken at the slip and speed ratio behaviour. The new control method is described, followed by open and closed loop experiments and the results of application in a vehicle. Finally, the conclusions of the research are summarized.

VARIATOR AND CLAMPING FORCE CONTROL

The variator enables the CVT to stepless change ratio between Low and OverDrive (OD). It consists of a metal pushbelt that runs over a primary and secondary pulley, each with a fixed and movable sheave (**figure 3**).

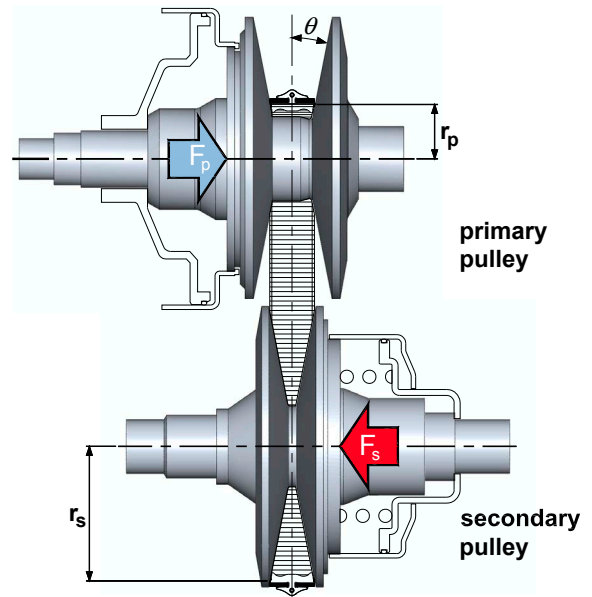


Fig. 3 P811 variator in Low speed ratio

The movable sheaves are actuated by hydraulic pistons that control the clamping force and speed ratio.

With a primary and secondary pulley speed ω_p and ω_s , the speed ratio is defined by:

$$i_s = \frac{\omega_p}{\omega_s} \quad (2.1)$$

A simple model for the maximum transmittable torque $T_{\max}$ is given by:

$$T_{\max} = \frac{2 \cdot \mu \cdot r \cdot F}{\cos(\theta)} \quad (2.2)$$

where r is the running radius, μ is the friction coefficient between belt and pulley, F is the clamping force, and θ is the pulley angle.

When the applied torque exceeds the maximum transmittable torque, slip between belt and pulley occurs. The minimum required clamping force on the primary and secondary pulley can be calculated by:

$$F_{\min,p,s} = \frac{T_{p,s} \cdot \cos(\theta)}{2 \cdot \mu \cdot r_{p,s}} \quad (2.3)$$

Since $T_p/r_p \approx T_s/r_s$, the minimum secondary clamping force can be written as:

$$F_{\min,s} \approx \frac{T_p \cdot \cos(\theta)}{2 \cdot \mu \cdot r_p} \quad (2.4)$$



The primary torque T_p is estimated by the engine controller. The primary radius r_p is derived from the speed ratio and variator parameters. The friction coefficient μ is taken constant or estimated online in a steady state situation [6]. To estimate an accurate minimum clamping force, a good model of the friction coefficient is indispensable [7]. In order to deal with torque disturbances and parameter inaccuracies that may lead to slip, a force is added to the minimum clamping force [8]:

$$F_s = F_{\min,s} + F_{\text{safety}} \quad (2.5)$$

with:

$$F_{\text{safety}} = 30\% \cdot \frac{T_{\max} \cdot \cos(\theta)}{2 \cdot \mu \cdot r_p} \quad (2.6)$$

This safety force (**figure 4**), is 30% of the clamping force needed to transfer the maximum torque $T_{\max}$. The safety factor S_f is defined as:

$$S_f = \frac{F_s}{F_{\min,s}} \quad (2.7)$$

The reduction of the safety force to improve efficiency and fuel consumption is the primary focus of this paper.

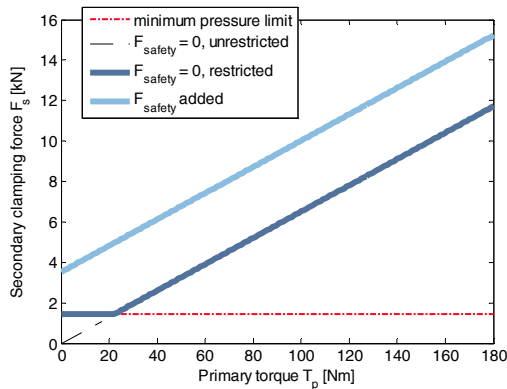


Fig. 4 Minimum clamping force and safety force, example for OD at 1500 rpm

VARIATOR RESEARCH, SLIP, SPEED RATIO

The reduction of safety force increases the risk of crossing the minimum clamping force which leads to macro slip. Excessive macro slip can result in belt failure by adhesive wear between belt and pulley [8]. Therefore, to optimize the clamping force, both efficiency and slip should be taken into account.

The absolute slip speed is defined as:

$$v = \omega_p r_p - \omega_s r_s \quad (3.1)$$

With the geometric ratio defined as $i_g = r_s/r_p$, the relative slip s_r can be written as:

$$s_r = \frac{v}{\omega_s r_s} \cdot 100[\%] = \frac{i_s - i_g}{i_g} \cdot 100[\%] \quad (3.2)$$

In [8] a slip control method was proposed based on this relative slip. The speed ratio i_s was derived from the available speed signals. The geometric ratio i_g was calculated from a measured geometrical variator property. Despite positive results ([1]), the geometric sensor accuracy, needed to control the slip sufficiently accurate, proved troublesome.

The variation of slip over the torque, ratio and temperature range complicated the definition of an accurate slip set-point in real-time.

For these reasons the research at Bosch-VDT focused on alternative control methods.

EXPERIMENT

First, the effect of clamping force on both slip and efficiency was investigated. During an experiment on a variator test rig, the clamping force was decreased until macro slip occurred.

Figure 5 shows the clamping force, slip and efficiency. This experiment was performed on a P811 variator in OD at a primary speed of 1400 rpm and an input torque of 70 Nm.

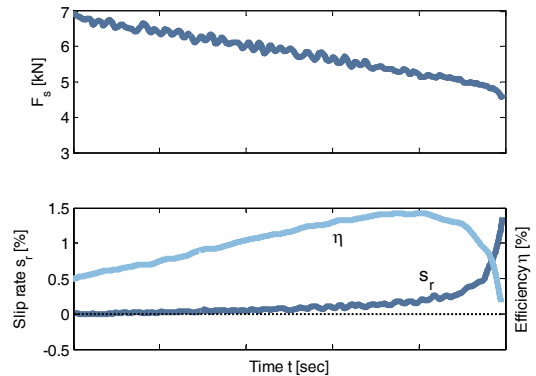


Fig. 5 Experiment with reducing clamping force F_s

When eq. 3.2 is rewritten, the speed ratio depends on slip and the geometric ratio as follows:

$$i_s = i_g + s_r \cdot i_g \quad (3.3)$$

Figure 6 shows the speed ratio, the geometric ratio and the slip value.

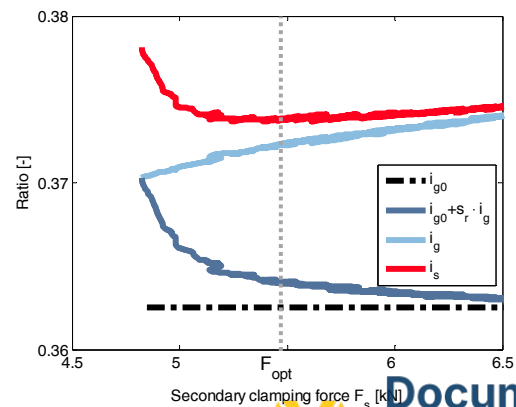


Fig. 6 Slip and ratios in OD