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THEORETICAL ASPECTS ON THE MULTI-REGIME FRICTION CVTs' DYNAMICAL BEHAVIOR

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Abstract: *Including a friction variator, the continuously variable transmission (CVT) can steplessly adapt the transmission ratio to take any value between two limits. For that, automotive propulsion systems incorporating CVTs ensure comfort, dynamic performance, driveability and may reduce the fuel consumption, chemical pollution and greenhouse effect emissions through a more efficient use of the engines. Unfortunately, the efficiency of the friction CVTs is generally smaller as the gear transmissions efficiency.*

Intending to reduce the CVTs' efficiency disadvantage, new CVT solutions are studied or already used in automotive applications. Many of these ideas deal with new structures of the power flows inside the CVT. Such transmissions able to change the number and orientation of its power flows, known as "multi-regime CVTs", can increase their overall efficiency because only a part of the input power passes through the variator, another part passing, with minor losses, through conventional mechanical path, as gears or drive chains.

This paper presents the main problems involved by the use of multi-regime CVT and also proposes some solutions for these. Aspects on transmission's kinematics and dynamics, as transmission ratio, efficiency, torque conversion, geared neutral, power circulation and couplings management are discussed. It is also indicated a way to transform a CVT in an infinitely variable transmission (IVT).

Keywords: friction variator, CVT, power-split, multi-regime, IVT, power circulation, kinematics, dynamics

Introduction

For any transmission, the speed ratio (gear ratio) is defined as:

$$i = \frac{\omega_i}{\omega_o} \tag{1}$$

where ω_i and ω_o are the rotational (angular) speeds of the input and output shafts.

Very useful can be also, mainly for graphical representations, the inverse of the speed ratio:

$$x = \frac{1}{i} = \frac{\omega_o}{\omega_i} \tag{2}$$

A continuously variable transmission (abbreviated CVT) is a transmission able to steplessly change the speed ratio $i_t = \omega_i / \omega_o$ of its input and output shafts. The speed ratio can be continuously varied by the CVT in a range limited by the extreme values of the transmission ratios (the minimum ratio $i_{min} = i_{OD}$ and maximum ratio $i_{max} = i_{UD}$), imposed by its design characteristics. Here and further, the indices OD and UD mean “overdrive” and “underdrive”.

The transmission’s working possibilities are well characterized by these extreme ratios, but also by the ratio spread D defined as:

$$D = \frac{i_{\max}}{i_{\min}} = \frac{i_{UD}}{i_{OD}} \tag{3}$$

Another very important functional parameter of the CVT is the efficiency η, which is the ratio of the output power P_o and input power P_i:

$$\eta = \frac{P_o}{P_i} = \frac{T_o\,\omega_o}{T_i\,\omega_i} = \frac{T_o}{T_i}\frac{1}{i} \tag{4}$$

where T_o and T_i are the torques acting on the transmission’s output and input shafts.

The core element of any CVT is the variator, i.e. that subassembly capable to steplessly modify the transmission ratio. Applying equation (4) to the variator, it observes the ability of that device to modify the output torque T_o versus the input torque T_i, if the speed ratio i_v is changed. That means the variators are a subcategory of torque converters, devices capable to change simultaneously the rotational speed and the torque.

Considering the kind of power used for the conversion, the variators used today in the automotive vehicles can be of different types: mechanic (with friction), hydrodynamic, hydrostatic or electric.

Even this paper deals with friction variators, the sentences presented here can be easily extrapolated to the other types of variators.

Friction CVTs

Compared with a gearbox (that is a torque converter using gear wheels), able to realize only few transmission ratios, the variator presents the main theoretical advantage of speed ratio’s continuous variation: an infinite number of possibilities to adapt the engine’s working point (characterized by the current speed and torque) to the instantaneous power need of the automotive vehicle. Thus, fitted with a CVT, the engine could function more efficient as in the case of an engine-gearbox combination, ensuring less fuel consumption, pollution and emission of gases with greenhouse effect.

That is the reason the research of the variators accompanied the entire evolution of motor vehicles. For many times, the friction variators were studied, experimented, applied for short time and finally abandoned, mainly for reliability and control problems. But today, the friction variators, included in modern CVTs, have reached the needed maturity to enter largely on the automotive market. And this happened due to the significant improvements obtained on the last thirty years in the fields of materials, lubricating liquids, tribology and control theories and devices.

There were imagined many types of friction variators, some of them being largely used on the motor vehicles: variators with pulleys and (push or pull) belt, variators with input and output shafts in direct contact, variators using rigid rotating-bodies interposed between the input and output shafts (as semi-toroidal, full-toroidal or cone-ring variators) and others. All these variators use the friction to transfer the power. To generate the needed friction forces, certain amount of slip and enough clamping forces must be applied in the contact surfaces. The instantaneous value of the friction coefficient depends on the slip ratio and on the tribological type of friction (dry, elastohydrodynamic or with intermediate properties).

The main power losses of a mechanical variator working on the friction principle consist in:

- loss of speed, caused by the relative slip appearing between the surfaces in contact (it reduces the output rotation speed);

- loss of torque, due to the rolling friction (drag) of the contacting rotating parts or of the bearings and trough the interaction of the rotating parts with the lubricant and the air inside the case (it reduces the output torque).

These loss types will diminish the variator's mechanical efficiency. Despite the effort of the researchers to reduce them, the global loss in a friction variator is few times bigger as the loss in a gearbox.

The variator' shaft-axes can be coaxial (as on the toroidal variators), parallel with an offset distance (as on the belt or cone-ring variators) or at an angle. That shaft positioning has implications on the general layout of the CVT and on its arrangement on the vehicle.

The variator isn't able to invert on command the rotation of its output shaft and also realizes transmission ratios into a range close to the value $i_V = 1$ (and so, for small ratios, the CVT's output speed can be too high). Moreover, the ratio spread $D = 5…6$ generally is not sufficient for motor vehicles with heavier working conditions.

For these (and other) reasons, the variator itself is not enough to obtain a power transmission useable for automotive propulsion. Due to that, to realize the functions of a conventional transmission, a CVT must include generally not only the variator, but also a starting device (as a hydrodynamic torque converter), an inverter with actuation couplings (usually a clutch and a brake), a parking brake, an electronic control system, a hydraulic actuation system. More than that, the CVT usually includes in the same case the axle's subassemblies: the final drive and the differential.

Joining all these subsystems, present CVTs demonstrate real advantages when are combined with a conventional engine: dynamic performances, comfort, driveability, low levels of vibrations and noise and even better fuel economy and reduced emissions. Also, the ancient problems of durability, maintenance and speed ratio control are definitively solved.

However, the two previously-mentioned main-disadvantages of the friction variators (the insufficient ratio spread and the reduced transmission efficiency) continue to represent the concerns for the engineers designing CVTs. One possible solution for these can be represented by the power-split systems.

Power-Split CVTs

The splitting of the power flow is a method by which the power is transmitted by two or more paths inside a (mechanical) transmission. This method of power transfer was proposed for the first time in 1987 to be implemented to the CVTs [1]. Because the transmission has an input and an output, it is necessary to be included into the transmission both a splitting device and a summation device. Usually, one of them is a planetary gearset, because this mechanism can be arranged in the transmission scheme either for splitting or for summation of power (it also exist the idea to replace the planetary gearset with a planetary mechanism obtained from a full toroidal variator at which the intermediate rollers are kept at a fixed tilt angle and the roller support – the carriage – is rotating [10]). The second device can be quite simple: a shaft that has mounted on it a gear wheel, a sprocket for a transmission chain or a pulley for belt.

Between the splitting and summation devices will be the paths for power transfer, composed by machine elements and mechanisms transmitting rotational motion, from which at least one is a (friction) variator.

Such a power-split transmission is able to combine the advantage of the continuous speed ratio change on the variator path with the advantages of bigger torque loads and better efficiency, obtained on a usual transfer path (consisting only in shafts and gear wheels). Another benefit can be represented by the transformation of a CVT into an infinitely variable transmission (IVT). That becomes possible by enlarging the finite ratio spread of the variator (**figure 1**, upper side – the green line) into an infinite one of the new transmission (**figure 1**, upper right side – the red line) and by translation of the ratio extreme values (**figure 1**, upper side – the blue and red lines).

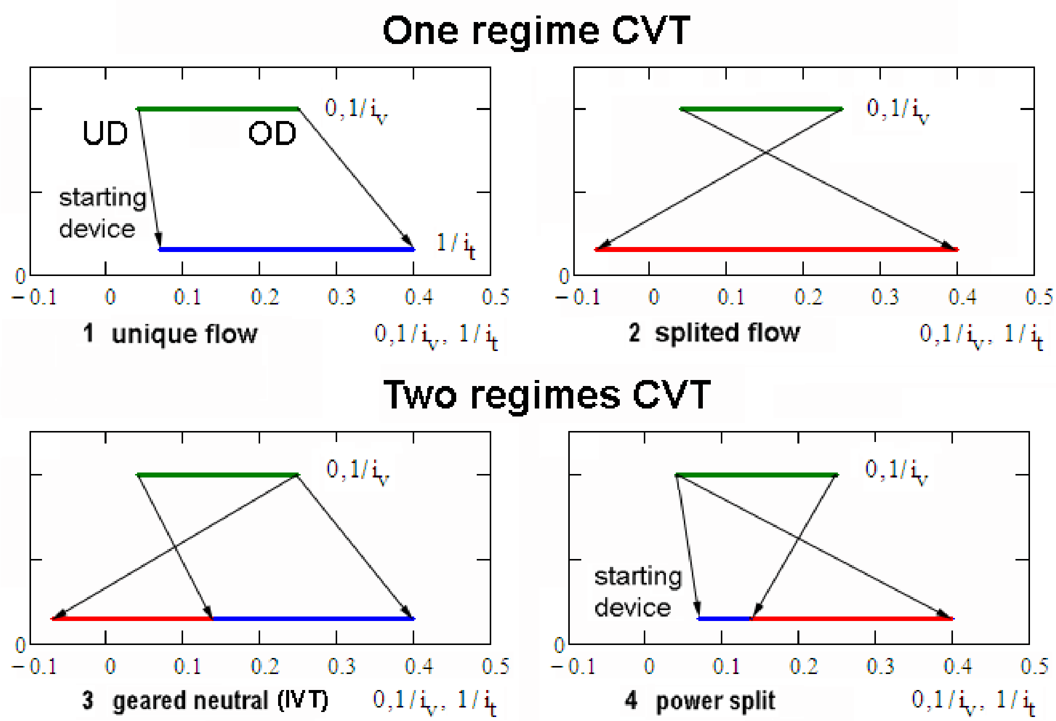

Fig. 1. Examples of possible transposition of the variator's speed ratio into the CVT's overall speed ratio

If during functioning the CVT can modify the structure of its power flows (for example, can work either with only one flow or with many flows), that is named a multi-regime transmission. In the case of such CVT, the speed-ratio spread is covered many times by the variator (two times by a two-regime CVT, as in **figure 1**, bottom side).

Many schemes can be imagined to split the power flow inside a transmission and such schemes are intensively studied at present to obtain functional advantages for the new types of CVTs [3], [4], [5], [6], [7], [8], [9], [10].

Normally, the power is split at a shaft level. Then, one flow passes through the variator and the other through some device having a fixed ratio (or more devices, having stepped ratios). Finally, at the output, the two power flows are combined through a planetary unit (epicyclic gear mechanism).

Function of the speed ratios of the conventional path and of the variator, and also function of the internal ratio of the planetary gearset, the power passing one path (of the variator or the other) can circulate in a direct way (from the input shaft to the output shaft) or vice versa, in inverse way, (as recirculating power).

For exemplification of the power-split, a hypothetic CVT scheme, presented in the **figure 2**, will be considered further. The components are the variator (with a variable ratio i_v), two pairs of gear wheels working in series (with the overall fix ratio i_f) and the summation device consisting in a planetary gearset (composed of the sun gear *a*, the planet-carrier *b*, the crown gear *c* and the planet gears). The signs (+ or -) of the speed ratios will be considered.

The power flows are outlined in the figure: the input flow P_i, the output flow P_o, the flow on the path with fix ratio P_f and the flow on the path with variable ratio P_v. The power flowing presented in the figure corresponds to a forward travel of the motor vehicle. If the vehicle is moving in reverse, the power flows P_f and P_v will be reversed.

In the case of forward driving (as is shown in the **figure 2**), due to the planetary gearset, the variator power flow is inversed: from the output to the input. That means the variator's power P_v will add to the input power P_i to pass through the fixed ratio path. In other words, the variator power P_v realize a closed circuit.

For that reason, this power is called recirculating power or parasitic power. But, the variator power is smaller as the input power ($P_v < P_i$) and that is an advantage because increases the variator working life through a smaller load. Although the power on the fix-ratio path exceeds the CVT's input power, due to the higher efficiency of the fix-ratio path, the power-split CVT can have a better overall efficiency as the one of a classical CVT (with all the power passing the variator).

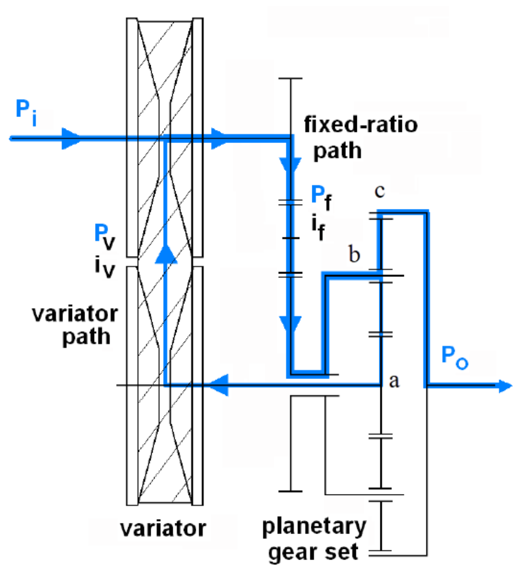

Fig. 2. Scheme of a power-split CVT

To find the CVT's speed ratio as function of the variator ratio, it can proceed as follows: starting from the input angular speed it calculate the angular speeds of the planet carrier *b* and sun gear *a*; then it calculates the angular speed of the output element, the crown *c*, using the equation of Willis, that describes the kinematics of any simple planetary units. Studying the **figure 2**, it follows:

$$\omega_b = \omega_i / i_f \tag{4}$$

$$\omega_a = \omega_i / i_v \tag{5}$$

$$\frac{\omega_a - \omega_b}{\omega_c - \omega_b} = i_h = \left(-\frac{z_s}{z_a}\right)\left(\frac{z_c}{z_s}\right) = -\frac{z_c}{z_a} \tag{6}$$

where i_h is the internal gear ratio of the planetary unit (from the sun gear *a* to the crown gear *c*, with locked planet carrier) and z_c, z_a and z_s are respectively the teeth numbers of the crown, sun and planet gears.

Introducing the equations (4) and (5) into the equation (6) and remembering that the CVT speed ratio is:

$$i_t = \frac{\omega_i}{\omega_o} \tag{7}$$

and the output shaft of the transmission is connected to the crown ($\omega_c = \omega_o$), it obtains:

$$i_t = \frac{1}{\left(1 - \frac{1}{i_h}\right)\frac{1}{i_f} + \frac{1}{i_h}\frac{1}{i_v}} = \frac{1}{(1 - x_h)x_f + x_h x_v} \tag{8}$$

Here, as indicated in equation (2), all the terms $x = 1/i$ represents the inverses of the speed ratios.

Figure 5.9 shows how the real numbers are distributed inverse scale transmission reports (1 / it) at the speed gearboxes (gear), the CVT and IVT.

IVTs - Infinitely Variable Transmissions

Considering the power-split CVT taken as example in **figure 2**, one can see that choosing appropriate speed ratios i_f and i_h (for the fix-ratio path and for the planetary unit) the denominator in equation (8) can take positive or negative values, including zero. If the CVT's speed ratio i_t is positive, the vehicle will move forward, and if it is negative, the vehicle will move in reverse (**figure 1**, upper right side). Such a transmission is known under the acronym IVT (infinitely variable transmission) and represents a transmission with continuous infinite ratio-spread.

When the variator speed-ratio has the maximum value (i_{vUD}, with the lowest output speed), the CVT will ensure vehicle's forward movement with maximum speed (the CVT's speed ratio is positive, with a minimum value $i_{tf} > 0$). When the variator speed-ratio has the minimum value (i_{vOD}), the transmission will ensure the vehicle's backward movement (reverse) with maximum speed (transmission's speed-ratio is negative and has the minimum magnitude $i_{tr} < 0$). By imposing these conditions in equation (8) it obtains a two-equations system

$$\mathrm{i_t}(i_{vUD}, i_h, i_f) = i_{tf} \qquad \mathrm{i_t}(i_{vOD}, i_h, i_f) = i_{tr} \tag{9}$$

from which it can be calculated the necessary speed-ratios i_f and i_h.

If the denominator in the equation (8) is zero, then the gear ratio i_t (of the power-split CVT) becomes infinite (sun gear and planet-carrier are rotating, but the crown remains stationary).

Putting this condition for the denominator, it can obtain the variator's speed-ratio, at which vehicle speed remains zero, while the engine is running and the transmission is engaged (i.e. the geared-neutral condition):

$$i_{vGN} = \frac{i_f}{(1 - i_h)} \tag{10}$$

The upper right side of the **figure 1** shows how the inverses of the CVT gear-ratios ($x_t = 1 / i_t$) are distributed on the real numbers' scale. Because the inverse of the speed ratio is proportional to the speed of the vehicle, this plot will correspond also to the travel speeds that could be achieved for any engine operating point (a pair of speed-torque values).

Multi-Regime CVTs

As can be observed from the example-CVT's scheme in **figure 2**, if ones eliminate the planetary unit and the power path with fix speed-ratio, the scheme would represent a CVT with a single power flow (where all the power passes the variator). To combine the advantages of both principle-schemes (for single power flow and split flow) it may use some coupling elements (most often able to allow engagement under load, i.e. power shift couplings) to interrupt or restore on the case one or more output flows. Thus are reached the CVT solutions with more operating regimes (multi-regime CVT).

Currently, there are published many results of researches which have as their object the continuously variable transmission with multiple operating regimes. Many schemes of multi-regime CVTs have been studied and some of which are already implemented in series production [5], [8], [10].

The **figure 3** presents a possible transformation of the one-regime power-split CVT (took as example in the **figure 2**) into a two-regimes CVT. This design, based on a pulleys and friction-chain variator, was figured-out and studied by the CVTs manufacturer LuK [3]. As can be seen, this scheme adds to the one in **figure 2** three couplings: two clutches (K_H and K_L) and one brake (B).

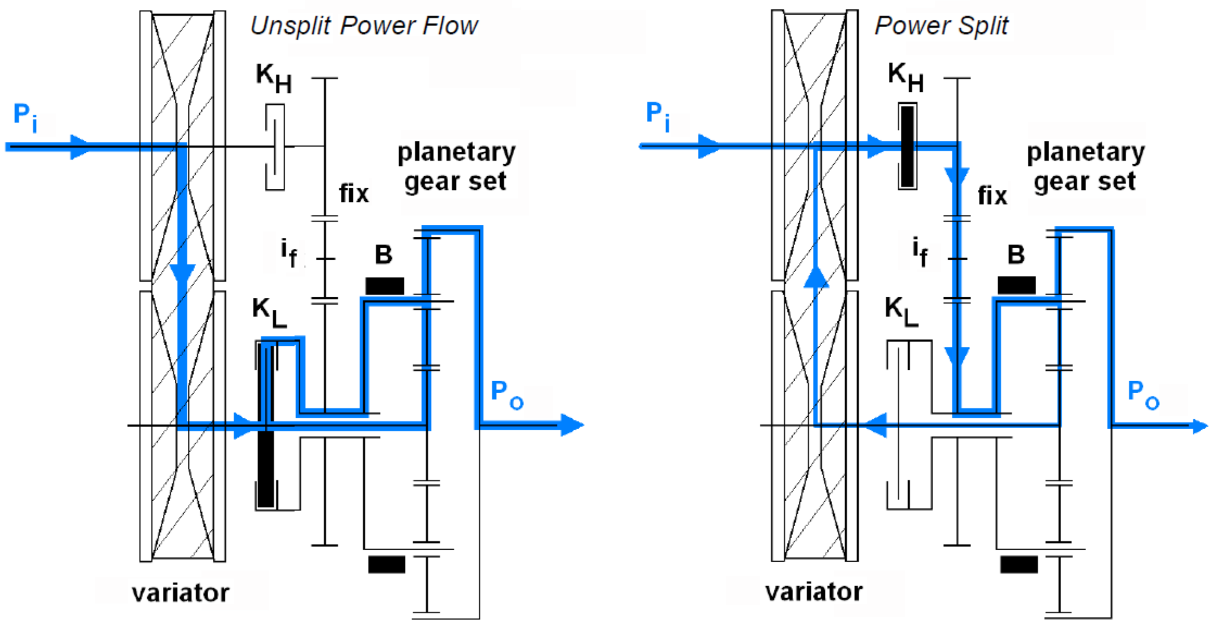

Fig. 3. Power of the engine at full load

Adopting appropriate values for the fix speed-ratio i_f and for the planetary-unit's internal gear-ratio i_h ($i_h < -1$), this scheme can operate at low driving speed with split power-flow and at high speeds with single power-flow (when become an IVT), or vice versa, with single flow at low speed and split flow at high speed. Both cases have advantages and disadvantages: the first loads less the variator in heavy-duty working conditions (at low speed) [10], but the second can provide better mechanical efficiency at high speeds (these situations are more frequent for normal cars) [5], [8].

The power-flow diagrams in figure 3 are similar for both variants (named further "example IVT" and "example power-split CVT"), but the indices H and L of the clutches indicate high and low speeds only for the case of power split. To obtain the power-split regime, the clutch K_H must be closed and the clutch K_L opened. In the inverse situation it obtains the classical situation with an unsplit power flow.

In the case of the "example IVT" functioning for the scheme in **figure 3**, the transmission can realize the "geared-neutral" condition and the vehicle can shuttle (switching between forward and reverse movement) without any clutch engagement or disengagement (**figure 1**, lower left side). That means in the scheme of **figure 3** it is no need for the brake B.

For the case of "example power-split CVT" (with power-split at high speed), the brake B is used to allow the vehicle's reverse movement (when the brake is opened, the vehicle moves forward, when the brake is closed, the vehicle moves backward). Because the clutch K_H is opened, the planetary unit behaves as an inverter, controlled by the clutch K_L and the brake B. These two couplings are used also as starting devices (the clutch K_L for forward movement and the brake B for reverse).

Kinematic and Dynamic Behavior of the Example IVT

To show the functional possibilities of a multi-regime CVT, further will be analyzed the dynamic behavior of the low-regime of the "example IVT". The corresponding power-flow structure is presented in the right-side of **figure 3**, where the brake *B* is excluded and the clutch K_L is opened and the clutch K_H is closed.

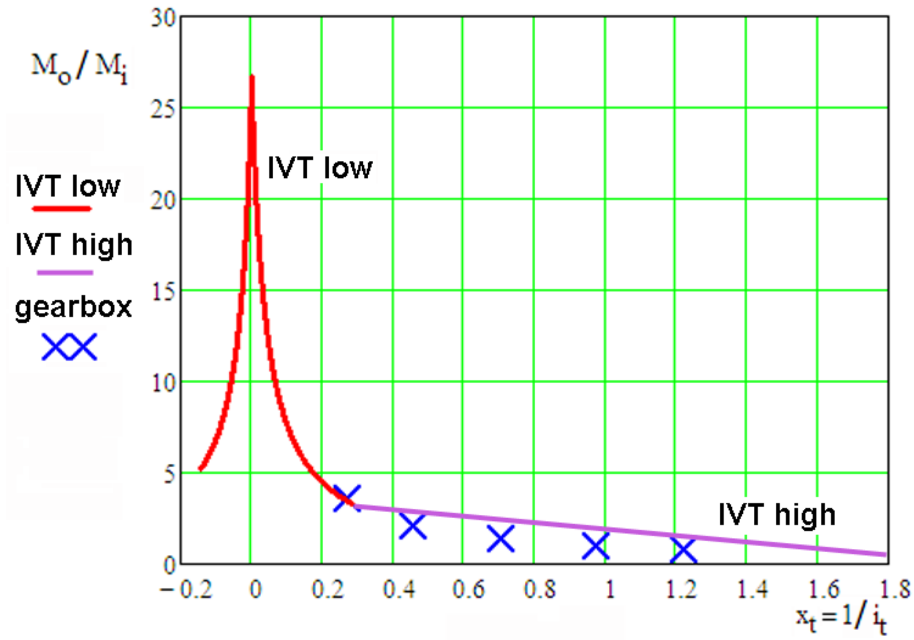

Fig. 4. Torque amplification as function of IVT (inverse of) speed ratio

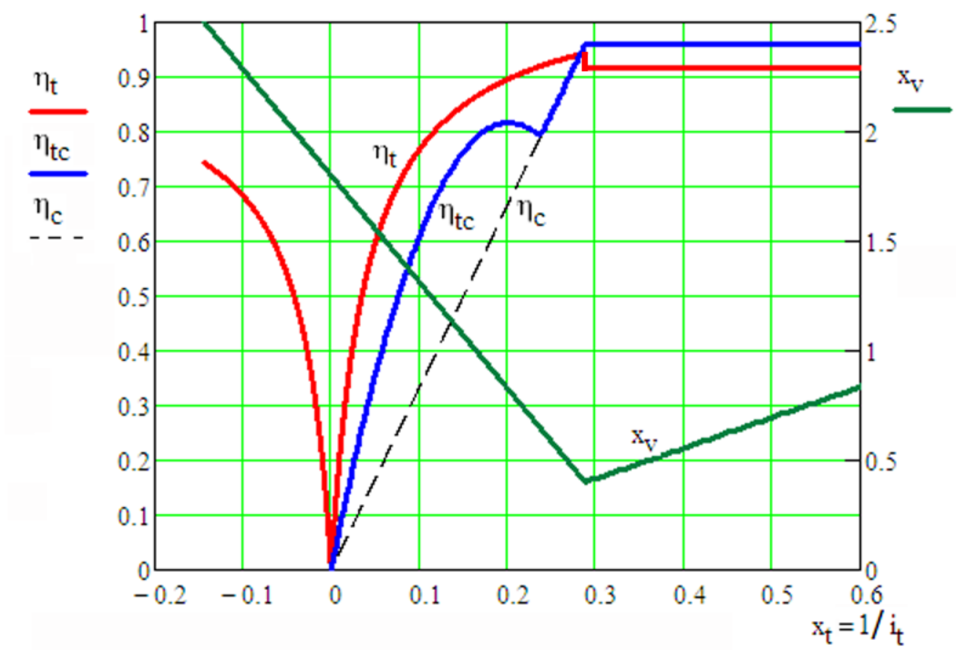

Fig. 5. Comparison of the mechanical efficiency for an IVT and a conventional CVT

To obtain the torques on each shaft, it will be applied the Newton second law for the rotation of the shafts. Also, the definitions of speed ratio and mechanical efficiency (equations 1 and 4) will be considered. The analysis will be made assuming steady conditions, which implies the shafts' angular accelerations will be zero. In these conditions it obtains the next system of equations:

$$M_i + M_v + M_f = 0 \qquad M_b = M_f\, i_f\, f(\eta_f) \qquad M_b = M_a\, i_v\, f(\eta_v)$$

$$M_a + M_b + M_c = 0 \qquad \frac{M_c}{M_a} = \frac{z_c}{z_a} \qquad M_o = M_c \tag{11}$$

In that system of six equations the significance of the notations is: M_i and M_o – the torques acting on the IVT input and output shafts; M_a, M_b and M_c – the torques on the shafts of the planetary unit; M_v – the torque on the variator primary pulley; M_f – the torque on the gear power path, near the variator primary pulley; z_a and z_c – the teeth numbers of the sun and crown gears; i_v and i_f – the speed ratios of the variator and gear power path and, finally, $f(\eta_v)$ and $f(\eta_f)$ – functions depending on the efficiency and on the orientation of the power flow (the true efficiency value η, for the normal power flow; the inverse of the true efficiency value, $1/\eta$, for the inversed power flow).

Based on the results obtained by solving this system of equations, **figure 4** presents the ratio of the IVT's output and input torques (M_o / M_i) as function of the transmission speed-ratio's inverse. Next vales were assumed for the mechanical efficiencies: $\eta_v = 0.92$ (variator); $\eta_f = 0.985^2 = 0.97$ (fix ratio on the gears path). One observes that at very low speeds, that ratio is very high (the greatest torque amplification is equal with 17 at the geared-neutral regime, i.e. when vehicle speed is zero). For comparison, there are marked in blue the corresponding points of an usual five-ratio gearbox for cars. The blue marker placed to the left side represents the torque gain for the first gear.

Figure 5 shows how the transmission's overall efficiency is influenced by the transmission's speed ratio. The red curve (η_t) corresponds to the "example IVT" (both for low and high regimes). The black line (η_c) and the blue curve (η_{tc}) correspond to a conventional gearbox fitted respectively with a clutch and with a torque converter.

The plots are indicating an evident advantage at low speed of the IVT over the gearbox (it was assumed $\eta_{gb} = 0.96$), both for efficiency (**figure 5**) and torque amplification (**figure 4**). Unfortunately, for the two regimes IVT, the efficiency at high speed (in the high regime) is smaller as the efficiency of the gearbox.

But even this disadvantage can be reduced or even eliminated if are considered CVTs with more than two regimes. Recent studies [10] demonstrate that further improvements of the overall efficiency and variator's load can be obtained by the use of CVTs with three or four regimes, maintaining the advantages of high torque amplification and geared-neutral.

Conclusions

Combined with actual or future engines, the friction continuously variable transmissions ensure comfort, dynamic performance and driveability, contributing to the diminishing of the fuel consumption and to the environment protection.

New CVT layouts are studied aiming to further improve theirs functional characteristics. One main research direction is the increase of the working regimes' number.

The last years showed that the multi-regime architectures used in automotive transmissions are good solutions for simultaneously increasing the speed-ratio spread, the transmitted torque, the mechanical efficiency and also to improve the vehicle driveability.

This article indicated a possible approach to study the kinematics and dynamics of a two-regime CVT, easily applicable to more complicated transmissions.

Some theoretical results obtained for a hypothetical two-regime CVT were also presented.

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