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DYNAMIC MODEL FOR THE PULL-BELT CVT SIMULATION

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ABSTRACT – The continuous variable transmissions (CVT's) permit to obtain any value of the transmission ratio between two limits. The continuous variation of the transmission ratio can be used to permanently adapt the engine functioning to the actual vehicle's movement conditions, promising important fuel efficiency increase and lower pollutant and CO_2 emissions.

On the other hand, this type of transmission is not an automatic one by its working principle, which means a change of the vehicle's road load will not automatically adapt the transmission ratio. Due to that inconvenient, extended researches are made today to improve the performances of the CVT's hydraulic or electric actuation systems, controlled both by mechanical and electronic devices.

The CVT's model presented in this paper was designed to represent the base for the study of different controlling algorithms' performances. The authors' intention is to include the CVT's control level in another higher control system of a hybrid propulsion system. Finally, some simulation results are also presented.

MANUAL TRANSMISSION VS. CVT

The continuous variable transmissions (CVT's) are transmissions incorporating a so called mechanical variator. Having a working principle based on mechanical friction, this device is used to adapt the engine's power parameters (angular speed and torque) to the instantaneous vehicle need.

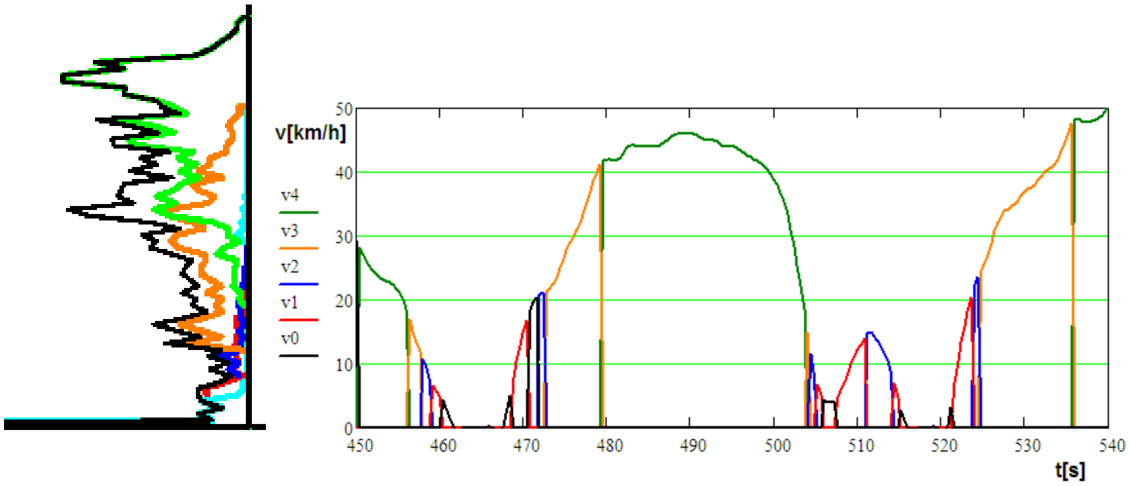

Fig. 1: Experimental data recorded in city traffic with a manual transmission car
right – record fragment of vehicle speed vs. time, with the emphasizing of the engaged gear;
left – relative probability density of the engaged gear vs. vehicle speed

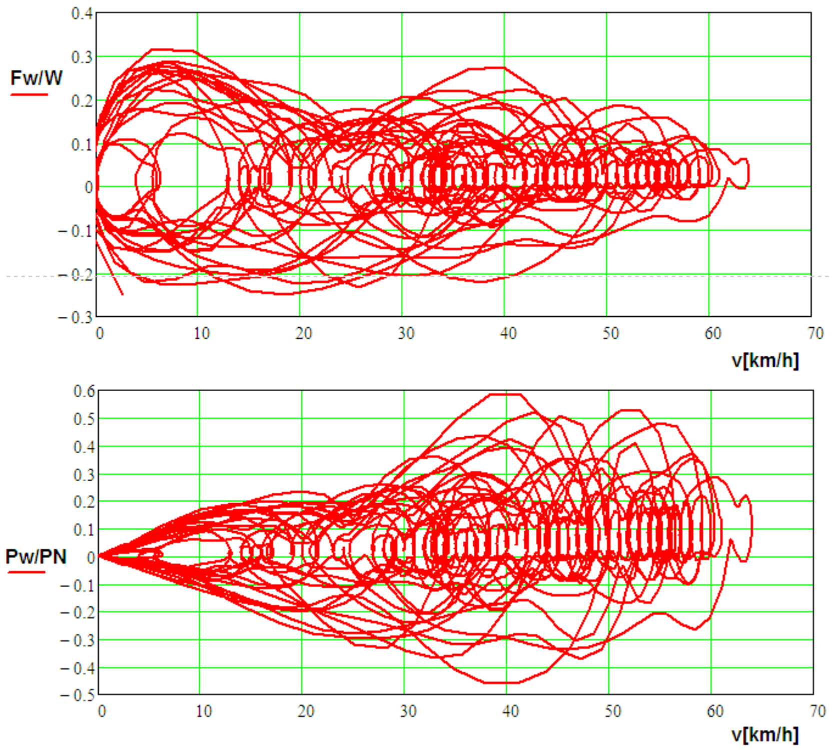

Fig. 2: Experimental data recorded in city traffic with a manual transmission car
up – force at the wheel (including braking) divided by the vehicle's weight vs. vehicle speed;
left – power at the wheel (incl. braking) divided by the engine's rated power vs. vehicle speed

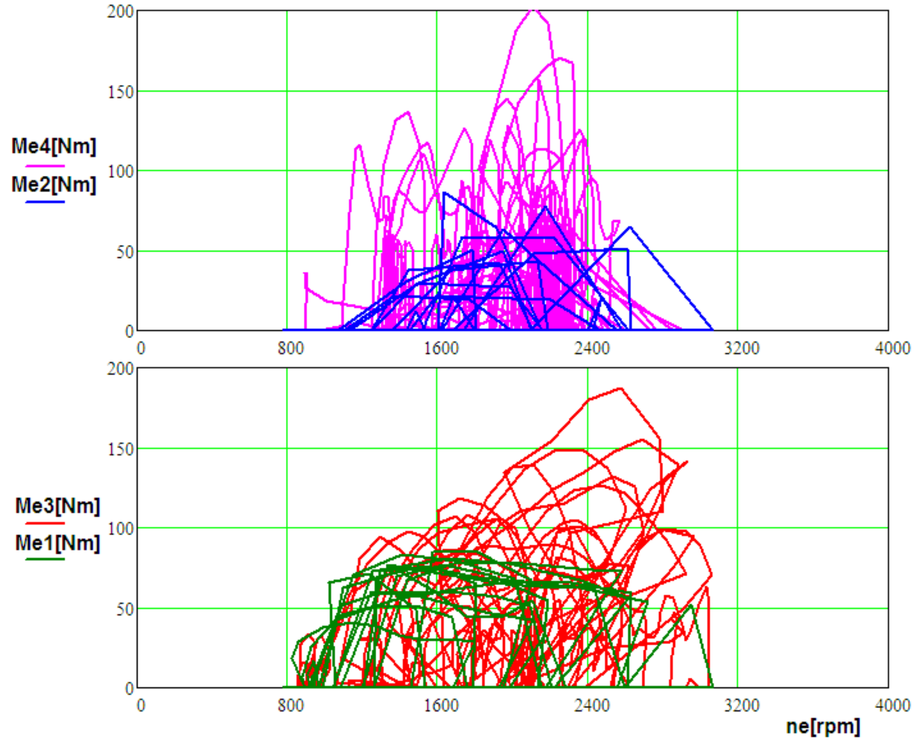

Fig. 3: Experimental data recorded in city traffic with a manual transmission car:
engine's torque vs. engine's speed in the four gear used (of five) during travel

If a conventional gear transmission can have only a discrete number of transmission ratios, the friction variator (the core of a continuous variable transmission) permits to obtain any transmission ratio between two extreme values. The infinite number of ratios between the angular speeds of engine and drive wheels gives to the CVT's a theoretical advantage over the gear transmissions, consisting in larger possibilities to choose, in different vehicle's functioning conditions, the optimal working conditions of the engine.

Figures 1, **2** and **3** show some experimental results recorded with a manual transmission car in the traffic of a big city, in normal rush hour condition (7). The plots in coordinates F_w-v or M_e-n_e show highly transient vehicle and engine behaviours, consisting mainly in cycles of acceleration and braking.

The length of the route of 9818 m was travelled in 1224 s, which means a mean vehicle speed of 28.9 km/h. In that time, 113 vehicle starts and 141 gear changes were performed by the driver: the 1st gear was engaged 33 times, the 2nd 29 times, the 3rd 25 times and the 4th 20 times. Also the neutral position of the gearbox was selected 34 times, from which 6 continued with the engagement of the previously disengaged gear. In other words, the driver effectuates 14.4 gear changes per km.

That statistical information means that, in our-days city traffic, the driver is stressed not only by the traffic situations but also by controlling its car. Also, the engine will have a lot of transitory regimes at low revs and loads.

The example presented can be a good reason for the replacement of the manual transmission with a transmission with continuous variation of its ratio, performed in an automated way.

LAYOUT OF THE CVT WITH CHAIN VARIATOR

A typical layout of the conventional CVT is illustrated in **Figure 4**. The engine drives a hydrodynamic torque converter, which is used for smooth acceleration at low speeds and can be closed above a certain speed with a lock-up clutch. One of the most known examples of a chain variator CVT, the Multitronic appearing on the Audi's cars, isn't equipped with a torque converter. Its function of helping the vehicle's start is taken by the reversing device (becoming now starting & reversing device), used to allow reverse driving. The main element of the CVT is the variator, using a pulled V-belt (tension chain) to kinetically link the input and output adjustable pulleys. The two-stage final reduction gear is needed to reduce the speed of the output pulley to the value needed for the vehicle's drive wheels.

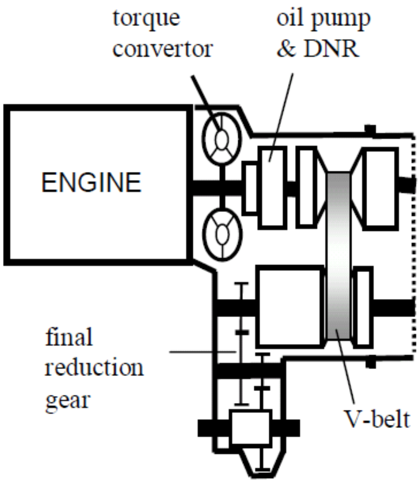

Fig. 4: Scheme of a conventional CVT with chain variator

The variator is formed by a power-transmitting steel link-plate chain (tension chain) that runs in an oil bath between two pairs of variable conical pulleys (3). The link-plate chain, consisting of a lot of link plates attached to a number of pins, can transmit torques by friction. Pushing the faces of the two conical pulleys closer together or moving them further apart causes the link-plate chain to run further towards the inside or outside of the pairs of conical pulleys. This actuation is used to produce continuous adjustment of the gear ratio, aiming to achieve the optimum in every driving situation.

The adjustment of the conical surfaces takes place hydraulically and is based on various control characteristics (6). A hydraulic “torque sensor” (automatic actuator, in fact) ensures that the link-plate chain is always correctly tensioned so that the torque is transferred without slip and without extreme chain stress. The hydraulic multi-plate clutch achieves better ride comfort and agility thanks to its electronic control. It also helps to reduce fuel consumption. If the driver applies the brakes when waiting at traffic lights, for example, the electronics reduce the tendency to creep forwards by decoupling the engine and the gearbox.

MODEL OF THE CVT WITH CHAIN VARIATOR

The first step in drivetrain simulation is to envision a **dynamic model**, which means to mentally replace the complex mechanical system with an assembly containing inertial elements (flywheels or translational masses) connected by idealized (without mass) shafts, springs or couplings (1).

The dynamic model must be complex enough to serve the aim of study and as simple as possible to be easily transposed in a mathematical model and then solved with no major difficulties (5).

Figure 5 presents the simplest dynamic model which can be used for the study of the car longitudinal dynamics. It consists of four flywheels, connecting shafts (having only stiffness as properties) and tree couplings (representing the clutch, the variator and the wheel-road interface).

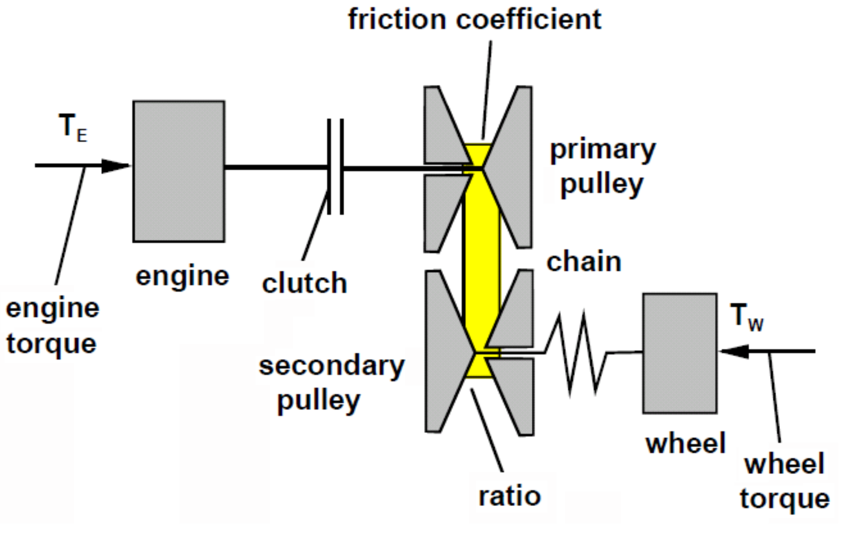

Fig. 5: The dynamic model of a pull-belt CVT for automotive vehicle (4)

The second step in drivetrain simulation is to obtain, and then to solve, the **mathematical model**. This represents a system of differential and algebraic equations that describe the dynamic behaviour of the studied system.
To obtain the mathematical model, it writes the movement equations for all the inertial elements. By solving these equations, there is firstly obtained the angular accelerations for each flywheel and then, by integration, the angular velocities and spaces.

The belt functioning is based on the Euler's relation that establishes the relationship between friction, tensile strength and the angle of winding on a conical surface of the belt. To obtain it on apply the second law of dynamics (the Newton's second law) considering stationary operation regime (constant speed, zero tangential acceleration and constant centripetal acceleration).

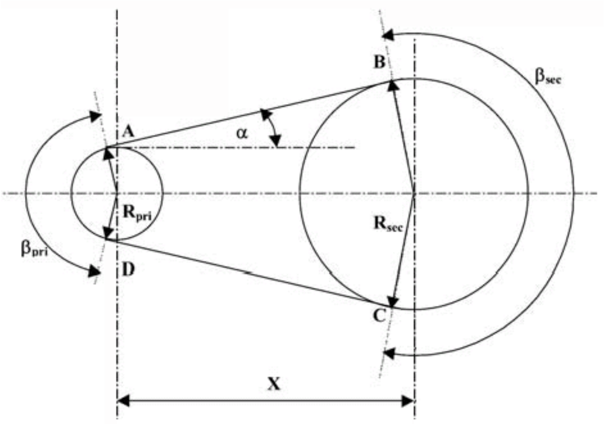

Fig. 6: Belt geometry during functioning

Figure 6 shows the idealized geometry of the belt. The indicated radii correspond to the average length from the belt side-contact surfaces to the pulleys' axes of rotation. From the current geometry, corresponding to a given operating point, it can be obtained the following expression for the length of the belt:

$$L = R_{pri}\beta_{pri} + R_{sec}\beta_{sec} + 2\sqrt{[X^2 - (R_{sec} - R_{pri})^2]} \qquad \text{(Eq. 1)}$$

where

$$\beta_{pri} = \pi - 2\alpha \qquad \beta_{sec} = \pi + 2\alpha \qquad \text{(Eq. 2)}$$

and

$$\sin\alpha = \frac{R_{sec} - R_{pri}}{X} \qquad \text{(Eq. 3)}$$

Since the free length of the belt, L, is known, as the distance between the pulleys centres, X, the previous equation of the belt length can be used to obtain the corresponding values of the radii R_{pri} and R_{sec} and angles α, β_{pri} and β_{sec} for any value of the belt-variator's geometric (theoretic or ideal) transmission ratio:

$$i_g = R_{sec} / R_{pri} \qquad \text{(Eq. 4)}$$

It should not be confused with actual transmission ratio i of the variator, which may differ from the geometric ratio because of contact slides occurring between belt and pulleys.

Using the ratio definition described above, a ‘high ratio’ or ‘overdrive’ condition is described by a ratio value, i, of less than one.

Using the last two equations one results:

$$\sin \alpha = R_{\mathrm{pri}} (i_{\mathrm{g}}-1)/\mathrm{X} \qquad \text{(Eq. 5)}$$

Now, the angles β_{pri} and β_{sec}, very important for the belt’s load capacity, can be determined as functions of i_{g}. In turn, the ratio i_{g} must be expressed as function of the current position of the actuator.

CONCLUSIONS

The paper presented a simple powertrain model of a vehicle with continuous variable transmission. This can be used to simulate the CVT’s functioning in order to obtain information about the stress level into the drive train, to optimize the control algorithms or to estimate the vehicle’s driveability, fuel consumption or pollution.

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