THE FUZZY LOGIC CONTROL OF ENGINE TORQUE AND SPEED IN THE POWERTRAIN WITH CVT

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Abstract
In this study the integrated control algorithm of the passenger car powertrain with continuously variable transmission (CVT) based on “fuzzy logic” is presented. This algorithm transfers the powertrain with unceasingly ratio changes to the powertrain with infinite number of virtual gears. Simultaneously, the control task has been reversed and the engine speed regulation with the engine torque regulation has been replaced. The results based on the simulation research shows that the drive-ability of the car has been significant improved without the fuel consumption increase.

1. Introduction
The CVT powertrain makes possibly an elastic control of the engine speed. However the potential of fuel consumption decrease in well-known solutions is not practically confirmed [1, 8, 9]. The lower mechanical efficiency of the “gearbox” is not only the cause [2, 3]. In many authors opinion [9, 10, 11], the main one of the enlarged fuel consumption is the powertrain control algorithm. Despite the significant progress, characterizing a new generation of the control algorithms [1, 4, 8, 9, 10, 11, 12], the possibilities of their improvement haven’t been exhausted. The original solutions characterizing the control algorithm which transfers the powertrain with unceasingly ratio changes to the powertrain with infinite number of virtual gears have been presented. The transmission ratio control was completed with the shift speed control. The high powertrain efficiency has been reached through the reverse of the control task. The engine speed regulation has been replaced with the engine torque regulation. This control algorithm has been realized with use of Fuzzy Logic Toolbox in the Matlab/Simulink environment.

2. Control problem
The best, from the fuel consumption point of view, is to keep the engine on the ideal operating line (E – line) [4]. However the torque reserve, on this curve, is not enough for a good drive-ability of the car (Fig.1). Inversely, keeping the engine on the dynamic operating line (D – line), leads to decrease the engine efficiency significantly (Fig.2). This characteristic conflict between the economic and the dynamic control strategy makes the problem of engine operating point selection very important [1, 5, 7, 8, 13]. The solution of that problem exerts an influence on working quality of the whole powertrain. The complexity of the problem heightens the necessity of regard to the transient processes and the dynamic of the transmission [1, 6, 14].
3. Integrated fuzzy logic control algorithm

The integrated control algorithm of the powertrain (Engine Torque and Speed Control - ETSC) is schematically depicted on figure 3.

The integrated control algorithm of CVT powertrain is based on a cascade of fuzzy regulators. The theoretical power \( P_t \), obtained from the fuzzy regulator RI, is dependent on an accelerator position, frequency and speed of its changes and temporary vehicle speed as well. This signal \( P_t \) simultaneously flows to Engine Speed Controller - ESC and Engine Torque Controller - ETC.

The ESC includes two fuzzy regulators. In the RII regulator the boundary values of the engine speed are determined; the highest engine speed value obtained in consequence of CVT ratio increase \( \omega_I \) and the largest engine speed value \( \omega_{II} \) shown in figure 4.
speed interval and having the full advantage of the torque reserve require the independent high efficiency and the power changes are realized by transmission ratio changes first of all.

So, the RII fuzzy regulator defines the ratio of virtual gear \( R_v \) and its length (engine speed increase \( \Delta \omega \) under constant CVT ratio).

The input signals of the RIII fuzzy regulator are the differences:

\[
\begin{align*}
 w_1 &= P_t(\alpha_p,v) - P_{100}(\omega) \quad (1) \\
 w_2 &= v - v^*(P_t) \quad (2) \\
 w_3 &= R_v - R \quad (3)
\end{align*}
\]

where:
- \( P_t \) – the theoretical power demand,
- \( P_{100} \) – the full load engine power,
- \( v \) – the vehicle speed,
- \( v^* \) - the constant vehicle speed at which the power resistance to motion is equal to the theoretical power demand,
- \( R \) – the CVT ratio,
- \( R_v \) – the virtual gear ratio.

The control of CVT is realized with use of the hydraulic unit (Fig.5). The pressure in the secondary pulley \( p_2 \), and the pressure ratio \( \xi \) are chosen with regard to:
- value of input torque,
- value of transmission ratio,
- shift speed value.

However the ESC control algorithm transfers the powertrain with unceasingly ratio changes to the powertrain with infinite number of virtual gears, the engine speed changes with vehicle speed increase, doesn’t mean the resignation of economic strategy [4]. The engine is kept on the ideal operating line (E) with use of regulator RIV (Fig.3). The output value of that regulator (degree of throttle inclination) is a function of engine speed. This way the control task has been reversed. So a free programming of engine speed is possible with keeping its high efficiency and the power changes are realized by transmission ratio changes first of all.

In the proposed algorithm the engine torque is not exclusively regulated. Limited engine speed interval and having the full advantage of the torque reserve require the independent torque control. The independent torque control takes place in case of:
• small power correction,
• high shift speed,
• minimum engine speed or boundary CVT ratio.

Fig. 5. Hydraulic unit of CVT

4. Mathematical model

For the verification of proposed algorithm, based on simulation method, a mathematical model was formulated. The mechanical model is shown in figure 6. The main elements of the model with four degrees of freedom are:
• mass associated with engine and with torque of inertia \( J_1 \) and angle of rotation \( \varphi_1 \),
• mass associated with clutch and with torque of inertia \( J_2 \) and angle of rotation \( \varphi_2 \),
• mass associated with driven wheels and with torque of inertia \( J_3 \) and angle of rotation \( \varphi_3 \),
• mass of the vehicle and rolling wheels with torque of inertia \( J_4 \) and angle of rotation \( \varphi_4 \).

The symbol \( \varphi_2 \) means the angle of rotation of final drive output wheel. In the model the wheels slip, mechanical losses \( (T_m) \), stiffness \( (k) \) and damping \( (d) \) was considered. The dynamic engine torque \( (T_d) \) from the one side and the torque of resistance to motion from the other side, are the inputs signals.

The CVT, in comparison to stepped gearbox, introduces an additional degree of freedom – the shift speed. So, the CVT ratio \((R)\) is an integral of shift speed in the model.

The dynamics of CVT was described with Ide model [6]

\[
\frac{dR}{dt} = k\left(\frac{i_p}{i_r}\right) \omega_1 \cdot A_2 \left(\frac{A_1}{A_2}\right)_r - \xi_d \]

(1)

where: \( \xi_d \) the thrust ratio, determining the shift speed as a function of thrust ratio.
5. Verification of control algorithm

5.1. Research method

The powertrain control algorithm requires multi-aspectual valuation [10]. Regarding the described conflict between economic and dynamic control strategy [4], vehicle acceleration and fuel consumption in driving cycles has been analyzed. The research has been done with simulation method under Matlab/Simulink environment.

5.2. Simulation of the vehicle acceleration

The object of simulation was the vehicle with CVT and spark ignition (SI) engine. The simulations were executed for initial vehicle speed in range from 14 to 25 m·s⁻¹ (50 to 90 km·h⁻¹), and sudden accelerator movement to inclination in range from 30 to 100%. The example simulation results were depicted in figure 7.

![Figure 7](image_url)

*Fig. 7. Simulation results of the vehicle acceleration for a different accelerator inclination: a) \( \alpha = 75\% \), b) \( \alpha = 100\% \) with initial speed \( v = 50 \text{ km/h} \)*
The visible differences between these two test results from different value of virtual gear ratio (Fig. 8).

However the throttle inclination, dependent on the engine speed has a similar course for both tests (Fig. 9).

In the initial phase, the throttle inclination is enlarged to 100%, for getting a full advantage of torque reserve. In the final phase, beginning earlier for smaller power demand, the throttle is regulated in such way to follow the ideal operating line (E – line).

### 5.3. Drive ability index

The drivability index (DI), having in view the quantitative formulation of traction properties of the car [12, 13], was defined as follow:

\[
DI = \frac{a_z}{a_i} \cdot \frac{a_{sr}}{t_i \cdot (j_1 + j_2)}, \tag{5}
\]

where

\[
a_{sr} = \frac{(v_2 - v_1)}{t_2}. \tag{6}
\]

The DI’s value was specified on the base of parameters characterizing courses of vehicle speed, longitudinal acceleration and acceleration derivative (Fig. 10). In the figure 11 the drivability index is depicted as a function of average longitudinal acceleration for the different powertrain control algorithms. As could be seen, the value of DI depends on powertrain control algorithm indeed. In case of conventional control algorithm (E and D strategy), consisting in CVT ratio regulation, the value of DI for dynamic strategy is over twice lager in compare to economic strategy in the whole range of average longitudinal vehicle acceleration. The proposed integrated powertrain control algorithm enlarges the DI value in a range of smaller values of average longitudinal vehicle acceleration, where the DI value is much greater as in the case of dynamic strategy with conventional control algorithm.
5.4. Fuel consumption

The powertrain control algorithm valuation from the point of view of the fuel consumption was done on the base of the simulations of the vehicle movement in drive cycles. In the figure 12 the fuel consumption for different control algorithms is compared. As could be seen the fuel consumption is even a little smaller in the case of integrated fuzzy logic powertrain control with compare to fuel consumption with conventional economic control strategy.
6. Summary

The proposed integrated fuzzy logic powertrain control algorithm can significantly improve the vehicle drivability without the fuel consumption increase. The elasticity of the algorithm, similar to the stepped automated transmissions “in modus operandi”, can decide about the customer’s acceptance for CVT.

References