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AN ATTEMPT OF FUEL-OPTIMAL CONTROL OF SCOOTER CVT POWERTRAINS

PRÓBA OPTYMALNEGO STEROWANIA PRZEKŁADNIĄ CVT SKUTERA Z PUNKTU WIDZENIA ZUŻYCIA PALIWA

Abstract

In this paper the solution for fuel optimal control problem is presented. The results obtained during brake stand research of scooter powertrains show the significant values of brake specific fuel consumption for the velocity that is maximum for a scooter according to highway code. With the introduction of CVT gearbox in which the selection of gear ratio can be controlled according to the worked out strategy the solution for fuel consumption problem is possible. Electromechanical actuators ensure the selection of a gear ratio independently of engine revs. Such type of construction solution makes working out the suitable control strategy that ensures decreasing of scooter fuel consumption possible. In the paper the control strategy owing to which fuel consumption decreases by over 20% is presented. The strategy was worked out on the bases of fuel consumption map for a defined scooter exploitation model. The possibilities of realization of the worked out strategy were tested on the brake test stand.

Keywords: CVT, optimization, control strategy

Streszczenie

W artykule pokazano rozwiązanie problemu sterowania przekładnią do uzyskania minimalnego zużycia paliwa. Wyniki uzyskane z badań stanowiskowych układu napędowego pokazują znaczące wartości jednostkowego zużycia paliwa dla maksymalnej prędkości skutera zgodnej z przepisami ruchu drogowego. Stosując przekładnię CVT, w której wybór przełożenia może być sterowany zgodnie z opracowaną strategią rozwiązanie problemu znacznego zużycia paliwa jest możliwe. Elektromechaniczne siłowniki zapewniają wybór przełożenia niezależnie od prędkości obrotowej silnika. Takie rozwiązanie konstrukcyjne pozwala opracować strategię sterowania zapewniającą zmniejszenie zużycia paliwa przez skuter. W tym artykule prezentowana jest strategia sterowania zapewniająca zmniejszenie zużycia paliwa o 20%. Ta strategia została opracowana z wykorzystaniem mapy zużycia paliwa w określonym modelu eksploatacji skutera. Możliwości realizacji opracowanej strategii sterowania były testowane na stanowisku hamownianym.

Słowa kluczowe: CVT, optymalizacja, strategia sterowania

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1. Introduction [3, 4]

Continuously Variable Transmission (CVT) is more and more often used in automotive application. Large transmission ratio coverage enables the engine to operate at more economic operating points. For every power level in internal combustion engine, there is one speed torque combination which achieves optimal fuel efficiency. Using continuously variable range of transmission ratio a line connecting these operating points can be followed for high drive unit efficiency. In spite of this, the use of CVTs in the automobile industry has remained marginal. Two-wheeler and snowmobile are major sections of automotive industry using CVTs. In this application a rubber dry belt is commonly used. Dry belts are usually used because a high friction coefficient is established between a belt and pulleys so that clamping force can be much smaller than it is in lubricated variants. Unfortunately, the problem which appears in non-lubricated belt pulley contact results from the lack of cooling of this contact, which causes high limits to the torque capacity of this type of variator. But these types of CVTs can be small and light and ideal for application in small motorbikes and scooters. Moreover, hydraulic control of the CVTs axial thrust that is most often used is not necessary and that is why hydraulic losses are eliminated. Despite these advantages CVTs are perceived as the most inefficient transmission system. It is the result of the application of mechanically controlled variators. Centrifugal rollers and torque cams have been widely used in rubber belt CVTs as the mechanical actuators. The performance of CVT depends on the characteristics of these actuators. By using mechanical actuators it is impossible to shift the transmission ratio in such a way as to make speed-torque combination point remain on an engine optimal operating line.

2. Optimal Operation Line [1, 2, 5]

Optimal Operation Line tracking is the most fuel economical way to operate the driveline. The OOL as shown in Fig 1, can be calculated from engine map by minimazing fuel consumption for a set of output power values. The real operation line (ROL) is also presented in Fig. 1 (spotted line). A big difference between these lines can be observed. Maximum scooter velocity is reached by 8500 rev/min of the engine. The brake specific fuel consumption (BSFC) value at this point is very high. This big difference is the consequence of a mechanical governor employed. To ensure the tracking of a OOL the special electromechanical actuator system has to be employed. However, the tracking of OOL influences the scooter drivability due to the lack of its dynamic response. Since drivability is also important for ratio control design, the special strategy should be worked out for a good combination of fuel economy and drivability.

Focusing solely on the BSFC values that represent the engine's thermal efficiency is not sufficient because considerable power loss occurs in the drive line. When the electromechanical actuator is used, the optimization of clamping forces can be possible and power loss due to the belt deformation can be lower.

3. Ratio control strategy

From the OOL the optimal engine speed for a given throttle position can be obtained. For the tested engine it is very difficult to approximate OOL line by using a simple function of

engine rpm. Approximation problems appear very often especially in popular small motorbikes and scooter two stroke engines. The real operation line is beyond engine high efficiency area. Unfortunately, the change of a gear ratio in order to obtain the scooter maximum velocity at lower rpm can cause noticeable diminishing of scooter performance. Moreover, there is possibility to increase the range of typical scooter CVT by about 10% only. However, this change is still too small to obtain noticeable improvement of engine – CVT drive system efficiency. The required power of scooter drive system to reach its limited maximum velocity is 30–40% lower then the maximum power of the employed engine. It allows the designers of a scooter drive system to take into account the possibilities of application of the partly opened throttle for maximum scooter velocity. Introducing electromechanical actuators can improve the drive system efficiency because gear ratio is no longer a function of engine revs. To obtain noticeable diminishing of fuel consumption value the change of gear ratio is necessary. The ratio control strategy of CVT should ensure slight lowering of scooter performance together with simultaneous significant lower fuel consumption. The way of the exploitation of such a vehicle is different from the exploitation of other vehicles. These vehicles move usually with wide opened throttle(WOT) from small velocity to maximum velocity. This way of scooter motion requires taking it into consideration when the ratio control strategy of CVT is evaluated. In this case to diminish fuel consumption, the engine revs corresponding to maximum scooter velocity should be lowered to 6800 revs/min.
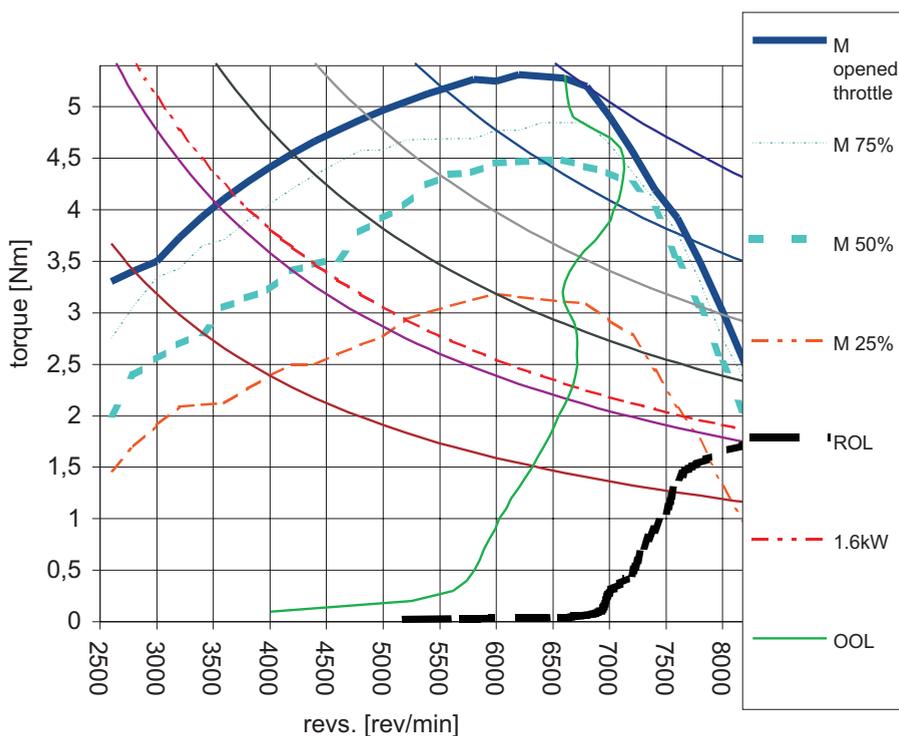

Fig. 1. Optimal Operation Line

Rys. 1. Optymalna linia współpracy

In order to obtain this value of engine revs the gear ratio should be lowered by about 20%. The value of BSFC is the smallest one at these revs. As the power of an engine at 6800 revs/min exceeds the power calculated from scooter motion resistance the position of engine throttle has to be diminished. In other case the scooter velocity will exceed permitted velocity. The engine work with partly opened throttle will be sufficient. Partly opened throttle causes further lowering of fuel consumption. Employing an electric throttle is essential here.

4. System modeling

The drive line is modeled only in its longitudinal behaviour and no drive train elasticities are taken into account. Fig. 2 shows a sketch of this system.
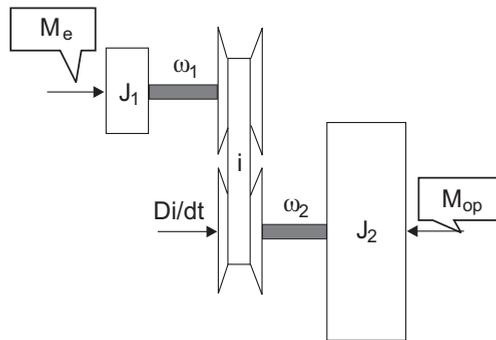

Fig. 2. Drive train structure

Rys. 2. Model układu napędowego

The gear ratio of the CVT is defined by

$$i(t) = \omega_2 / \omega_1$$

The equations of powertrains motion are the follows:

$$M_e - M_1 = I_1 \frac{d\omega_1}{dt}$$

$$M_2 = i(t) \cdot M_1$$

$$M_2 = I_2 \frac{d\omega_2}{dt} + M_{op}$$

where:

I_1 – inertia moment of an engine,
I_2 – equivalent inertia moment of a scooter,
M_e – engine torque,
M_1 – input moment to CVT,
M_2 – output moment out CVT,
M_{op} – resistance moment of motion.

When in motion, city scooters equipped with small power engines have usually wide opened throttles. The control strategy should take into account the character of the drive which in fact is composed of extreme acceleration, drive with constant speed, breaking and reaccelerating until the maximum velocity is reached. This cycle is repeated several times; in each case the time in which the vehicle velocity is constant is different. Two values that define the run of the cycle are: the angle of opened throttle and the real gear ratio of CVT. When CVT is considered, the third value – the rate of gear ratio should be taken into consideration. These three values may be used in the control strategy of electromechanical actuator.

The start-on is the same for both types of steering systems. The centrifugal clutch is used for the start on. Subsequently the vehicle is accelerated until the velocity corresponding to engine revs slightly higher than maximum torque is reached and then the change of a ratio in CVT begins until the minimum ratio is reached. The balance of power on a scooter wheel with power of motion resistance defines vehicle velocity. This balance appears when the revs of the engine are much higher than revs of the engine for maximum power. These revs which are much higher are caused by the necessity of achieving the maximum vehicle velocity. The difference between engine revs of maximum torque and maximum power for typical engines which is very small is the reason why engine revs should be much higher than revs of engine maximum power. It is necessary for gaining a wider range of velocity changes. Unfortunately, it results in the increase of vehicle fuel consumption. Moreover, the value of resistance power is on average 40% smaller than the maximum value of power of the engines When an actuator is mechanically steered the ratio value is the function of engine revs and thus its value is defined by a regulator structure. When electromechanical actuator is used simultaneously with electric throttle the characteristics of the engine can be better employed and the fuel consumption can be lowered. The use of electromechanical actuator should ensure the same or at least similar performance as in the traditional version. As lowering fuel consumption requires smaller revs of an engine it is indispensable to lower total gear ratio of a vehicle. On order not to change the drive power too much the vehicle acceleration should be done with possible high value of engine torque. When CVT with electromechanical steering is considered there is a possibility of steering the rate of gear ratio change. When the rate of the gear ratio change is controlled the whole process of acceleration can be performed with constant engine revs as it appears in revs of a engine maximum torque. In such cases, even when total gear ratio is lowered, it should ensure good performance.

The control strategy is as follows: scooter accelerates with CVT low ratio till the engine reach the revs slightly higher then revs of maximum torque. Then the gear ratio starts to change with rate ensures the constant engine revs. When the maximum velocity is reached ,the change of a gear ratio will be carried out simultaneously with diminishing the throttle angle to make engine power balance the resistance power of motion .This control method was implemented in the model described above. The control run simulation is presented in Fig. 3.
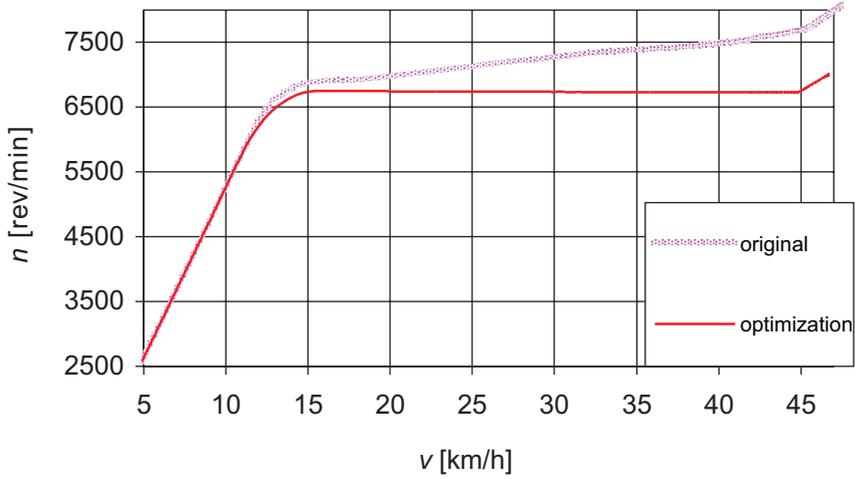
Fig. 3. Control strategy
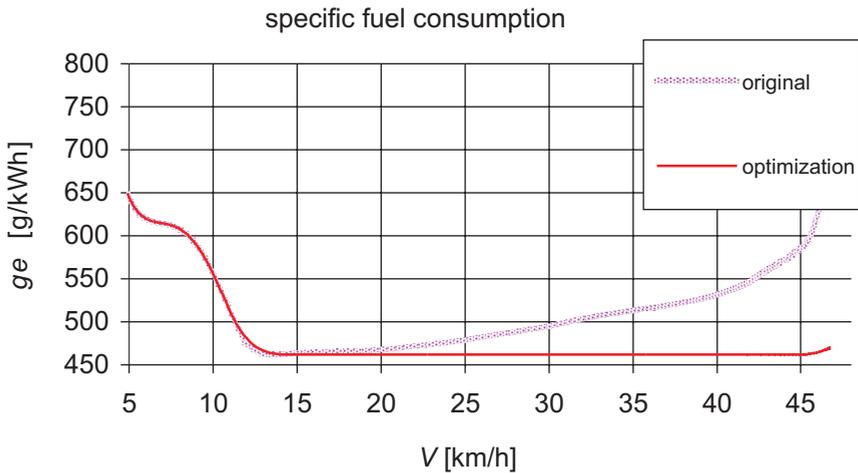
Rys. 3. Strategia sterowania

Fig. 4. Specific fuel consumption

Rys. 4. Jednostkowe zużycie paliwa

The results of applying this control method to the mathematical model of drive train are presented in Fig. 4 and 5. The characteristics shown in Fig. 4 present that when the velocity is 45 kmh, specific fuel consumption decrease using this control strategy is about 20% when compared with traditional method. Since, as it was stated before the velocity of these types of vehicles is close to 45 kmh, such lowering of specific fuel consumption is also the case when fuel consumption per hour is considered.
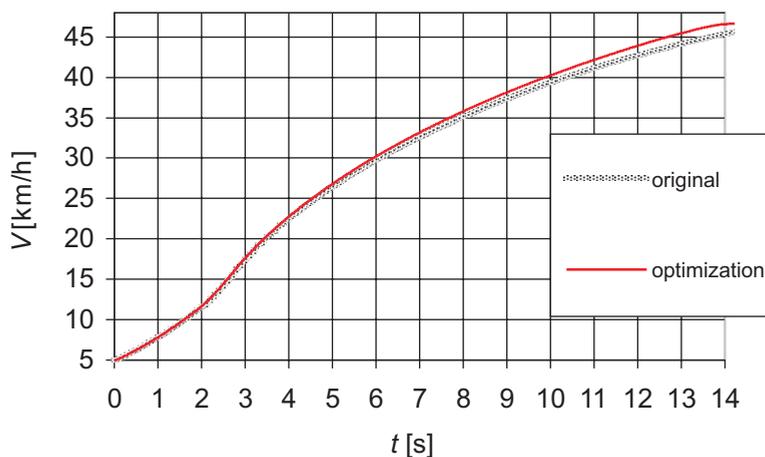
Fig. 5. Performance of scooter

Rys. 5. Osiągi skutera

As it can be seen in fig.5 the performance of vehicles is the same.

5. Conclusion

1. The employment of electromechanical actuator makes working out of any control strategy for application of CVT possible.
2. The worked out strategy of CVT steering ensures improvement f scooter efficiency by lowering its fuel consumption.
3. The worked out CVT steering strategy ensures scooter performance that is comparable the performance of scooter with mechanical steering CVT.

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