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Control and operating conditions and hydrokinetic converter slip in the vehicle’s transmission system

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Abstract. The study concerns the slip test occurring between the pump and the turbine of automotive hydrokinetic converter. The tests were carried out on the MAHA MSR 500 test bench using a vehicle equipped with a hydrokinetic transmission ZF 4HP20 contained torque converter with adjustable lock up clutch. The paper presents the influence of the different gear change and converter control strategies as well as different load levels on the slip phenomenon between converter pump and turbine. As demonstrated by the analysis of the test results, some control strategies allow for a significant slip phenomenon, which may result in a significant decrease in the overall transmission efficiency. However, the use of an adjustable lock up clutch allows on the other hand such a control that significantly reduces the converter slip phenomenon, while blocking the pump and turbine already at low vehicle speeds can significantly affect fuel consumption, especially in the urban driving cycle.

1. Introduction
Vehicle manufacturers are constantly improving the individual elements of the vehicle's powertrain system. One of the important goals of these activities is in addition to obtaining solutions characterized by high durability and comfort of use and also to improve ecological and economic properties. The powertrain system consisting of 2 basic subassemblies of the unit or drive units and the transmission system is constantly developed. In recent years, there has been a significant development not only of powertrain units, but also of transmission components. There are a number of solutions available on the market ranging from classic gearboxes MT (Manual Transmissions), through their automated solutions AMT (Automated Manual Transmissions) and further developed versions in the form of DCT (Dual Clutch Transmissions) as well as CVT (Continuously Variable Transmissions) to hydro-mechanical transmissions AT (Automatic Transmissions).

As the market analyses show, users are more and more often opting for the choice of such solutions in the powertrain system, which allow automatic selection as well as automatic shifting. As the statistics show in recent years, the global market share for vehicles with AT is higher than 30%. If, on the other hand, other types of automatic transmission are taken into account, their share in the global market exceeds 50%. In some markets the share of AT powertrains is over the last years significant. As the forecasts show (Figure 1) in year 2018, in Europe it will be 17% and in the US 67% vehicles with AT powertrains [1]. Also in other countries and regions being large automotive markets, such as Japan, China or NAFTA countries, among the automatic transmission systems (AMT, AT, CVT, DCT), AT solutions are dominant, which is manifested by a very large number of vehicles equipped with it [2]. At the same time, there are many activity to improve the operating indexes of automatic transmissions, in particular: efficiency [3], drivability [4], and better cooperation with the combustion engine [5].
In the case of application as powertrain unit an internal combustion engine, it is necessary to use in the transmission system components that allow the vehicle to move and drive at low speed. These tasks are met by placing such components in the transmission system as friction or hydrokinetic clutch. Most often, is used a hydrokinetic transmission or an automatic controlled friction clutch, as an intermediate element between the engine and the transmission. The necessity of using such additional elements cooperating with the internal combustion engine, in particular the torque converter, causes a decrease in the efficiency of the entire system and as a result, in deterioration of economic and ecological properties. Despite the adverse effect on economic properties, the hydrokinetic transmission is still very often used due to its advantages in the form of high comfort of use, high drive torque available when moving the vehicle, good properties when driving with the trailer and additionally high durability.

2. Research problem

2.1. Pump and turbine operating condition
The use of large number of gear ratios in modern hydro-mechanical construction increase the range of gear changes, which allows the combustion engine to work near its optimal working areas. It should be noted, that there is still a need to use a torque transmission element between the engine and the transmission in order to be able to move the vehicle and drive at low speed. The work of such an element, usually in the form of a hydrokinetic converter, causes losses in the transmission system. They are caused among other things by the slips occurring between converter pump and turbine. With the decrease of this slip, the efficiency of the transmission system increases.

Examples of maps for the pump and turbine containing characteristics of the torque transmitted by the torque converter pump and turbine were presented by Lechner and Naunheimer [6]. The shaping of these maps by means of design changes or the method of hydraulic fluid flow control allows to achieve the desired characteristics of the hydrokinetic transmission

2.2. Hydrokinetic transmission with lock-up clutch
Ejiri presented the characteristics of efficiency $\eta$, the degree of torque conversion (torque ratio $\mu$) and (torque capacity coefficient $t$) considering the blocking action of the relative pump and turbine movement in the case of operation of the lock-up clutch [7]. In previous hydro-mechanical constructions of automatic transmissions, the lock-up clutch was engaged exclusively on the 3th or 4th gear. In the current solutions, the lock-up clutch operation covers all ratios, and the engine speed at which the converter pump and turbine are locked within 1100 - 1700 rpm. In modern solutions the lock-up clutches operate with a slip, which is additionally controlled with the closed-circuit torque converter [8]. The operation of blocking the pump and turbine has a clear effect in the form of torque converter increased efficiency, which value may theoretically approach almost 100%. The process of switching the lock up
clutch was modelled and mathematically described by Koralewski, Wrona [9]. Asl, Azad, and McPhee dealt with, modelling of torque converter torque conversion taking into account the operation of the lock-up clutch. The results of the conducted simulations show the effect of the lock-up clutch on the significant improvement of the overall torque converter efficiency [10], while Chiwon and others presented the concept of slip control strategy for automatic transmission vehicle taking into account the operating of lock up clutch, pointing out the possibility of reducing fuel by approximately 3%, simplifying transmission construction and reducing costs [11]. The dynamic sliding process for the hydrodynamic torque converter was modelled in the Matlab-Simulink environment by Jin-Hyuk and Hoon [12]. As the authors show, it is possibility to create a reliable model that can be used as an observer for dynamic sliding process control.

3. Experimental setup

3.1. Research object and test bed
As test object was selected Citroen C5 with 3.0 V6 engine and hydro-mechanical automatic transmission ZF 4HP20 equipped with lock-up clutch with controlled slip and auto adaptive gear change strategies. Selected parameter of tested transmission configuration are presented in the table 1.

Table 1. Selected parameter of tested Automatic Transmission ZF 4HP20 [13]

| No | Parameter | Value |
|----|-----------|-------|
| 1  | Maximal load | 330Nm |
| 2  | Transmission ratio gear 1 | 2,718 |
| 3  | Transmission ratio gear 2 | 1,481 |
| 4  | Transmission ratio gear 3 | 1,000 |
| 5  | Transmission ratio gear 4 | 0,720 |
| 6  | Transmission ratio gear R | 2,568 |
| 7  | Final drive | 3,450 |
| 8  | Torque converter | Hydraulic with lock-up |
| 9  | Lock-up | 2nd, 3rd, 4th gears with controlled slip |
| 10 | Gear change programs | Multiple programs: auto-adaptive (DSP) Sport - Snow |

The tested automatic transmission is electronically controlled (ECU – Electronic Control Unit) and has implemented auto adaptation laws (DSP – Dynamisches Schalt Programm) with 3 thru driver selected programs: Normal (D) - an algorithm which adjust the operation of the automatic transmission to the vehicle load and promotes economical fuel consumption, Sport (S) - control algorithm which concentrates of sporty driving, Snow (D*) algorithm which suited to driving with low adherence [14].

The analysis of transmission operating indexes was performed on the basis of the research conducted on a MAHA MSR 500 chassis dynamometer at Opole University of Technology. The transmission slip is calculated as follows:

\[ s = \frac{(n_{in} - n_{out})}{n_{in}} \cdot 100\% , \]

where

- \( n_{in} \) - pump rotational speed, rpm
- \( n_{out} \) - turbine rotational speed, rpm.

and the pump and turbine rotational speeds are measured with rotational speed sensors located nearby converter pump and turbine.
3.2. Research scope

In order to investigate the effect of variable transmission operating conditions on the pump and turbine slip value, test cycles with a variable speed value were created. First, the influence of the control program selection at the gradually changing vehicle speed (Figure 2) on the slip of the transmission was examined. The speed profile was graded every 5 km/h (1.389 m/s). Due to the expected greatest impact of the hydrokinetic transmission on the powertrain system operation indicators for lower driving speeds, the speed range was limited to values typical for urban driving (0 to 17 m/s). Influence of different control programs on transmission slip was tested at further described 3 different control strategies designed as: Normal (D), Sport (S), Snow (D*).

![Figure 2. Step speed as a test profile](image1)

In the following, the effect of transmission load on its slip was examined. For this purpose, 2 load levels were selected and wheel resistant force $F_i$ was given by the equation:

$$F_i = \frac{P_i}{v}$$  \hspace{1cm} (2)

where

- $F_i$ - wheel resistant force at $i$-load level, N
- $P_i$ - wheel resistant power at $i$-load level, kW
- $v$ - vehicle speed, m/s.

The resistant power load level was selected at values $P_1 = 5$ kW and $P_2 = 20$ kW. The curve of wheel resistant force and power was presented on figures 3 and 4.

![Figure 3. Transmission load – wheel resistant force and power curve at load level $P_1 = 5$ kW](image2)
Figure 4. Transmission load – wheel resistant force and power curve at load level $P_2 = 20$ kW

As described in (2) the wheel resistant force is depend on vehicle speed and wheel resistant power are constant at constant vehicle speed.

4. Experimental results

4.1. Transmission slip at different control strategies

Impact of control strategy at transmission slip was tested at control strategies designed as: Normal (D), Sport (S), Snow (D*). The slip value research results are presented on Figure 5.

Analysis of slip curves measured at different control strategies shows some differences. The largest differences in the transmission slip value were recorded for lower vehicle speeds of up to approximately 10 m/s. As the research results show, significant slip values refer to the control according to the Snow D* algorithm. At low vehicle speeds, the algorithm allows slip values greater than 20%. In turn, the algorithm D results in a significant reduction of the slip remaining below 10% throughout the test cycle. Controlling the transmission according to the algorithm appropriate for sports driving S the value of the gear slip is kept below 5%, and for the vehicle speed above 10 m/s the converter slip disappears.

In the final phase of the test, (after 220 seconds) the braking action of the transmission occurs, which is manifested by the negative transmission slip (i.e. the rotational speed of the turbine is higher than the rotational speed of the pump due to the transfer of load from the vehicle wheels to the converter turbine.
and engine with slip of up to 10%. Immediately prior to stopping the vehicle wheels, the transmission slips increase due to braking of the wheels when the braking system is used to stop them.

4.2. Transmission slip at variable load level

In the further part of the research, a slip was measured between the converter pump and the turbine at two selected transmission load levels marked as P1 and P2. The results of transmission slip measurements are shown in Figures 6-8.

![Figure 6. Transmission slip at control algorithm S](Image)

![Figure 7. Transmission slip at control algorithm D](Image)

The analysis of the experiment results shows that the increase in transmission load translates into an increase in its slip for all available control algorithms. Nevertheless, for the control program S the registered differences are noticeable but they are not large and additionally limited to total slip disappearance occurring at higher load level. In turn, the control for algorithm D shows the differences at slip curves for speeds below approx. 7 m/s, where for a higher load level P2 a slip of more than 20% was recorded, while for a lower level P1 the slip is below 10%.
Controlling the gearbox according to the D* algorithm manifests as the largest differences in the measured torque converter slip. Much greater slip value is noted for P2 load almost in the course of the entire test cycle. Only at the lowest and highest vehicle speeds of test cycle the differences in slip values can be treated as insignificant.

4.3. Analysis of transmission slip

In order to assess the slip more fully at given load levels and to apply selected control algorithms, the slip values corresponding to the quasi static load conditions of the transmission at constant vehicle speed were averaged. The result of this averaging are depicted as the measurement points shown in Figures 9 - 11.

Figure 9. Transmission slip approximation at algorithm S and a) P₁, b) P₂ wheels load level

Figure 10. Transmission slip approximation at algorithm D and a) P₁, b) P₂ wheels load level
Figure 11. Transmission slip approximation at algorithm D* and a) P₁, b) P₂ wheels load level

The points used in the graphs were used to create curves and the transmission slip course approximating equations depending on the vehicle speed.

Synthetic comparison of the transmission slip mean values was performed using the integration of the transmission slip curve obtained during the step speed test according to the following relationship:

$$\bar{s} = \frac{\int_{0}^{t} S(t) \, dt}{t},$$

where:

- $t$ - time, s

- $S(t)$ - transmission slip curve

Figure 12. Mean transmission slip with different control strategies and different wheel load level

The values of the average transmission slip show, on the one hand, the clear effect of the transmission load, and on the other hand the significant influence of the used gear control algorithm (Figure 12). Mean slip value at step speed test shows that the highest values oscillating around 30% occur in the control of strategy D* and the application of the S program shows significantly lower slip values not exceeding 5% even in the case of a larger load at P₂ level. Basic program D causes slip values within 5.48% to 16.52%, and the obtained values are much more dependent on the load level.

5. Conclusions

The conducted bench tests showed a significant influence of both the level of transmission load and the control algorithm used on the slip of the torque converter operating in the vehicle's powertrain system.

In the case of use the control algorithm S, the pump and turbine blocking during lock-up clutch was detected at the vehicle speed depending on the load in the range of approximately 7 - 10 m/s. In the case of use control strategy D, there is a significant reduction of the transmission slip over the vehicle speed of approx. 7 m/s to the value of approx. 3.5 - 4%, but also maintained at speeds above 16 m/s. In turn, the use of the D* algorithm is related to the operation of the transmission with significant slip from about mean 30% - also in the case of a low transmission load. Limiting the slip and blocking the pump and turbine with the lock up clutch on one hand allows improving the efficiency of the transmission, but on the other hand it makes it difficult to compensate for torsion vibrations coming from, among others,
the vehicle's engine. This can negatively affect the feelings of comfort and reduce durability transmission system components.

However, it should also be remembered about the impact of the engine's working area on the efficiency of the entire drive. Due to the high engine speed being maintained when using the S algorithm, the overall powertrain efficiency despite a significant reduction even if the transmission slip may be lower than with the D or D* algorithm. Achieving a compromise between the comfort of use and the efficiency of the powertrain requires advanced control or the use of additional elements suppressing torsion vibrations (e.g. torsion vibration dampers). Enabling the complete disconnection between torque converter and the engine can improve the efficiency of the powertrain, especially in the urban driving cycle. Such solution with additional elements disconnected engine and transmission with hydrokinetic torque converter increases the cost and complicates the construction of the transmission system. Nevertheless, it should be noted that it is possible to further increase the efficiency of the hydrokinetic torque converter, and thus reduce of fuel consumption - especially in the urban driving cycle.

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