FIELD TESTING OF AN AUTOMATIC TRANSMISSION (AT) OF AN OFF-ROAD VEHICLE

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Summary

The construction and principle of operation of the conventional ZF-4HP24 automatic transmission used in a Land Rover Range Rover P38A off-road vehicle has been discussed and results of field testing of the automatic transmission (AT) have been presented. Within the field tests, automatic transmission fluid (ATF) pressures were measured at diagnostic take-off points in the AT hydraulic system. Moreover, the ATF viscosity was determined (at normal operating temperature) for fresh fluid and for ATF samples taken from the AT under tests after a long period of normal operation of the transmission. The field tests were carried out before and after servicing the AT, during which the AT fluid and fluid suction filter were replaced. The field tests revealed that before replacement of the fluid and fluid suction filter, the AT operated incorrectly, especially when the normal ATF operating temperature was achieved.

Keywords: automatic transmissions (AT), automatic transmission fluid (ATF), kinematic viscosity, AT pressure test

1. Introduction

The modern automatic transmission (AT) is a complicated unit which requires appropriate operation and specialized maintenance. For most of the popular transmissions, the maintenance consists in periodical checking of the fluid level and adding of the automatic transmission fluid (ATF) if necessary [4, 12, 13]. Both vehicle operation experience and experimental tests [3] show that the fluid characteristics deteriorate with AT operation time and this has a negative impact on the functioning of such a transmission. Periodical replacement of the ATF and the fluid suction filter often makes it possible to restore correct AT functioning and to extend the time between overhaul of automatic transmissions. The maintenance work, however, must be done with due care and diligence to prevent contamination of the ATF and the hydraulic system with external substances [6, 7].

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ZF Friedrichshafen AG, which manufactured the automatic transmission under tests, recommends the ATF and the filter of the AT hydraulic system to be replaced after every 100 000 km travelled regardless of vehicle operation conditions and gearbox type [10]. Different recommendations are formulated by another AT manufacturer, i.e. Allison Transmission, which divides the transmission duty cycles into "general" and "severe". The AT maintenance procedures consisting of ATF and filter replacement are to be scheduled according to standard intervals that are defined as the numbers of kilometres travelled by the vehicle (20 000 to 240 000 km), the numbers of hours of vehicle operation (500 to 4 000 h), or time between maintenance (6 to 48 months). These figures depend not only on the duty cycle but also on the type of the automatic transmission involved [11]. The vehicle operation experience also shows that damage more often happens to the automatic transmissions that are mounted in vehicles with high-power engines of high torque output. It frequently happens in the workshop practice that replacement of working fluid and fluid filter in a malfunctioning automatic transmission brings the transmission back to full working order. For the servicing of an automatic transmission, high-quality replacement materials (automatic transmission fluids and fluid filters) recommended by the transmission manufacturer for the specific AT model should be used. The use of an inappropriate ATF or filter will result in damage to the automatic transmission [8]. The objective of this work was to carry out experimental tests that were to show whether the AT servicing consisting of the replacement of automatic transmission fluid and fluid suction filter would result in an improvement of operation of a malfunctioning automatic transmission after a long period of the transmission being in service (in a vehicle that travelled about 150 000 km). Within the experimental tests carried out during normal vehicle drives, ATF pressures were measured at diagnostic take-off points in the AT hydraulic system before and after servicing the AT.

2. Object of testing

The experimental field tests were carried out on a ZF-4HP24 automatic transmission used in a Land Rover Range Rover 4.6 HSE off-road vehicle for two cases as regards the technical condition of the transmission, i.e. before and after servicing the transmission. The transmission under tests was a conventional automatic transmission with a hydrokinetic torque converter and with four forward drive ratios and a reverse gear. In the automatic transmission model under test, the AT is controlled with the use of an EAT (electronic automatic transmission) system, where engine and vehicle operation parameters (load, accelerator pedal position, engine speed, vehicle speed) are taken as system inputs. The EAT system output signals govern the operation of the electrohydraulic AT controller, which directs the ATF flow to appropriate actuators that engage clutches and lock multidisc wet brakes to couple together or immobilize selected components of individual epicyclic gearsets. Apart from the gearbox proper, the ZF-4HP24 automatic transmission system includes other components, such as drive mode selector, electronic automatic transmission (EAT) controller, drive mode selector lever mechanically connected via a cable with the drive mode selector, and ATF cooler, which makes it possible to keep the ATF temperature close to 80 °C. The AT model under tests is provided with an "H gate" drive mode selector mechanism (Fig. 1b), which combines the functions of controlling the operation of the automatic transmission and a mechanical reduction gear engaged by means of an electric actuator. The high-speed ratios ("Hi") are obtained when the automatic transmission operates alone; for the vehicle to operate in the range of low-speed ratios ("Lo"), the mechanical reduction gear must be additionally engaged by shifting the selector lever to the side marked "Lo".

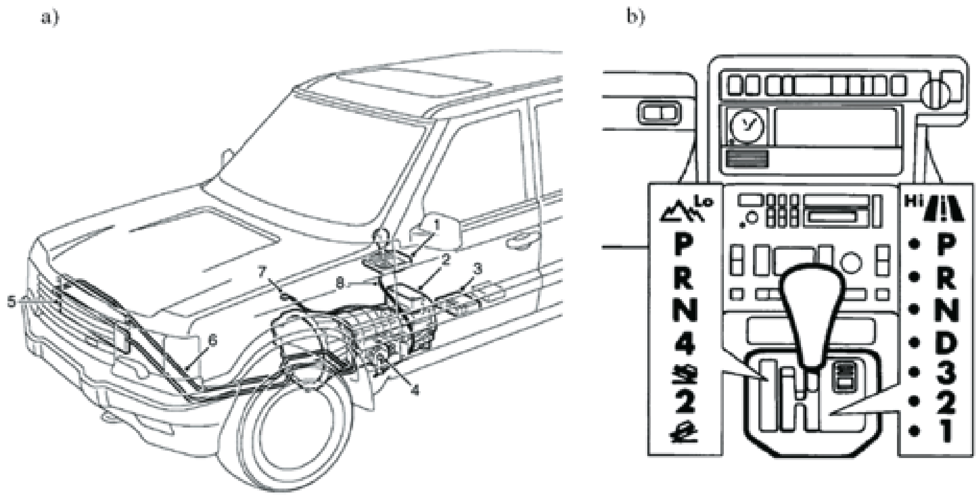
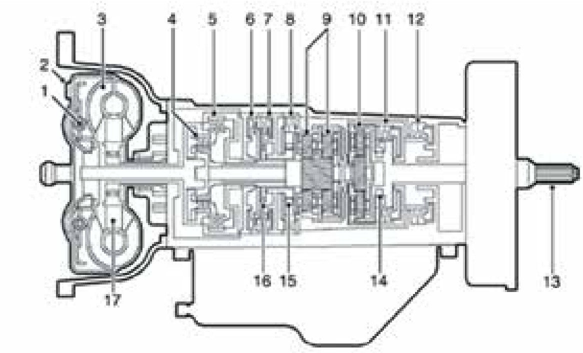


Fig. 1. The ZF-4HP24 automatic transmission system: a) automatic transmission component layout; b) drive mode selector lever assembly with an "H gate" mechanism [17];
1 – drive mode selector lever assembly; 2 – automatic transmission (AT) ZF-4HP24;
3 – electronic AT (EAT) controller; 4 – drive mode selector position switch;
5 – ATF cooler; 6 – ATF lines; 7 – AT breather tube; 8 – drive mode selector cable

The power and torque is transmitted from the engine crankshaft to the automatic transmission by a hydrokinetic torque converter [4, 5, 10–13, 20]. The torque converter consists of impeller integral with the pump body fixed through a drive plate to engine crankshaft, turbine connected with the gearbox input shaft, and stator. Adequate clearance between these parts is ensured by sliding thrust rings and bearings. The torque converter is completely filled up with the automatic transmission fluid. The ATF is drawn by the impeller through the passage around the impeller axis and is moved by centrifugal forces to turbine vanes. The kinetic energy of the ATF hitting the turbine vanes causes the latter to rotate, in result of which the energy is transmitted to the turbine and is converted into the energy of rotational motion of the turbine. Then, the fluid is again drawn to the space surrounding the converter axis, i.e. to the zone of lower pressure, and thus it returns to the impeller vanes. The ATF flow inside the torque converter depends on the difference between the rotational speeds of the impeller and the turbine. At high values of this difference, the ATF leaving the turbine hits the impeller vanes, trying to rotate the impeller in the opposite direction. Such a phenomenon would result in resistance to impeller motion, i.e. in energy losses, but it is eliminated by the action of vanes of the converter stator placed between the turbine and the impeller. The ATF flowing out of the turbine hits the front surfaces of the stator vanes, trying to rotate the stator in the direction opposite to that of impeller rotation. However, the stator is blocked by the action of a one-way clutch, i.e. it does not rotate; in consequence, the fluid flow direction is changed to boost the impeller rotation. The directed ATF flow inside the converter causes the torque applied as an input to the impeller to be doubled or even tripled by the converter at high values of the slip between the impeller and the turbine, which occurs during vehicle start-up or acceleration. On the other hand, it is worth remembering that the higher the slip, the lower the converter efficiency. At high slip, the energy of rotational motion of the converter impeller is partly transformed into heat in the automatic transmission fluid.



Gear	Ratio
1st	2.480:1
2nd	1.480:1
3rd	1.480:1
4th	0.728:1
Reverse	2.086:1

Fig. 2. The ZF-4HP24 automatic transmission: 1 – lock-up clutch; 2 – pump body with impeller ; 3 – turbine; 4 – multidisc forward drive clutch; 5 – multidisc reverse drive clutch; 6, 7, 8 – multidisc brake; 9 – Simpson epicyclic gearset; 10 – simple epicyclic gearset; 11 – multidisc clutch; 12 – multidisc brake; 13 – output shaft; 14, 15, 16 – freewheel mechanism (one way clutch); 17 – torque converter stator with one way clutch [17]

To prevent energy losses and fluid overheating, modern torque converters are provided with a "lock-up" friction clutch, which consists of a piston actuator and a friction disc. The piston can slide along the torque converter axis. When the piston moves towards the pump body, it presses the friction disc against the internal surface of the pump body for the pump impeller to be coupled with the turbine. The EAT controller outputs a signal which, operating a valve in the electrohydraulic controller, causes the ATF to flow through a passage in the turbine shaft to the piston actuator that engages the lock-up clutch. In the ZF-4HP24 automatic transmission, the lock-up clutch of the torque converter is engaged when the vehicle is driven with a speed of 48–72 km/h in the 4th gear [16]. The centrepiece of every conventional automatic transmission is a system of epicyclic gearsets, which implement specific gear ratios. Theoretically, a single epicyclic gearset can offer seven gearset ratios, including one direct drive and two reversing gears. In practice, two usable gearset ratios are obtained from one simple epicyclic gearset. For this reason, compound planetary gearsets are used in automatic transmissions, e.g. Simpson and Ravigneaux systems [4, 5, 16]. The ratios of the compound planetary gearsets can be changed by signals received from the EAT controller. The EAT system output signals operate the AT electrohydraulic controller, whose basic task is to generate fluid pressures of specific values in appropriate branches of the hydraulic system. The most important pressure is the main fluid pressure in the actuator supply line.

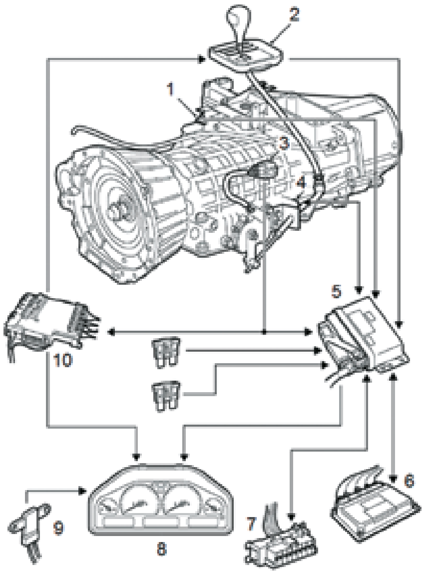


Fig. 3. Schematic diagram of the electronic system of the ZF-4HP24 automatic transmission: 1 – EAT controller connector; 2 – drive mode selector; 3 – drive mode selection signal connector; 4 – vehicle speed sensor connector; 5 – electronic automatic transmission (EAT) controller; 6 – engine control module (ECM) ; 7 – diagnostic connector; 8 – instrument pack; 9 – transmission fluid (ATF) temperature sensor; 10 – body electrical control module (BeCM) [17]

The value of the pressure in the actuator supply line is regulated depending on the torque transmitted to the turbine shaft and the resulting changes in loads of the multidisc wet friction brakes and clutches. Control valves direct the ATF flow to appropriate actuators that engage the multidisc wet clutches and brakes and to the piston actuator of the lock-up friction clutch. A manual valve (item 7 in Fig. 4) is operated by the driver by means of the drive mode selector lever. The clutches and brakes are engaged by solenoid valves MV 1 and MV 2 to change the gearbox ratios; the lock-up friction clutch of the torque converter is operated by solenoid valve MV 3. Solenoid valve MV 4 is a proportional valve and its task is to regulate the main fluid pressure in the actuator supply line for adequate gear-shifting quality to be maintained [19].

A hydraulic accumulator is assigned to each multidisc wet clutch and brake to reduce the effects of hydraulic surges and pulsations of the ATF in the supply lines of specific actuators [21].

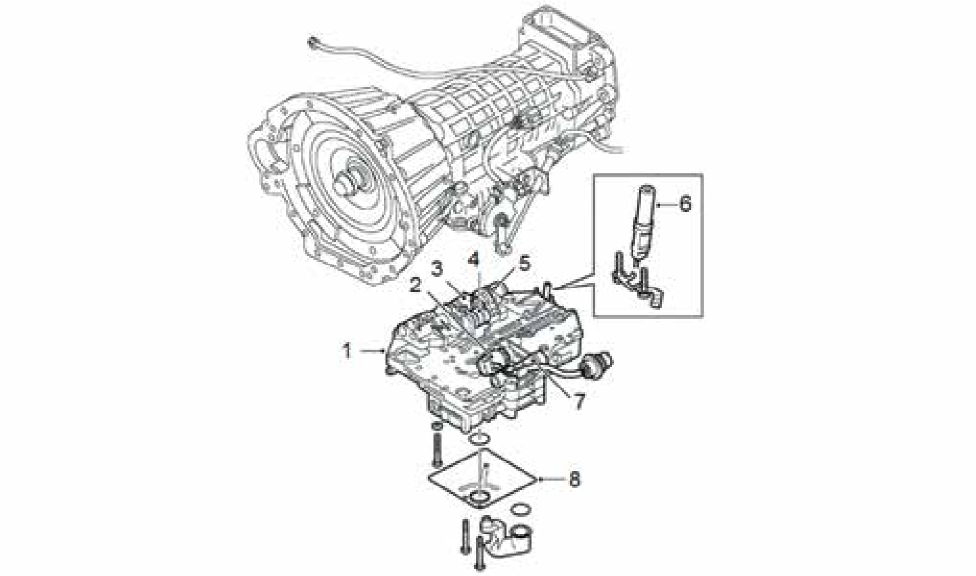


Fig. 4. Electrohydraulic controller: 1 – valve block; 2 – pressure-regulating solenoid valve (MV 4); 3, 4 – gear-shift control solenoid valves (MV 2 and MV 1, respectively); 5 – lock-up clutch control solenoid valve (MV 3); 6 – output shaft speed sensor; 7 – manual control valve; 8 – suction filter of the hydraulic system [17]

3. Experimental tests

The field tests consisted in measuring the main fluid pressure in the actuator supply line (p_{D1}) and the pressure in the torque converter (p_{D2}) at two diagnostic take-off points of the ZF-4HP24 automatic transmission. The test conditions were identical at the tests carried out before and after servicing the AT, during which a part of the AT fluid and the suction filter of the AT hydraulic system were replaced. During the AT servicing operation, only the fluid present in the transmission sump and the fluid gravitationally drained from the gallery of the hydraulic system can be replaced. The fluid present in the torque converter (about 20–25 %) and in the fluid cooler (5–10 %) will not be replaced. According to manufacturer's workshop manual [17], the AT should contain 11 dm^3 of fluid in total. When the transmission is serviced, only about 8 dm^3 of the fluid is replaced. During the transmission operation following the fluid replacement, the fresh fluid is mixed with the used fluid left in the AT unit. In some cases, e.g. in Mercedes cars, torque converters are provided with a separate converter drain plug. For the AT under tests, DEXRON III mineral hydraulic fluid in a distinctive red colour, with a kinematic viscosity of $\upsilon_{100} = 8$ mm^3/s at 100 °C, was used as the ATF, pursuant to manufacturer's workshop manual [17]. The tests were carried out with following the standard procedure of pressure measurements at diagnostic take-off points [12, 13] and with the use of a diagnostic instrument kit for the measurements of fluid pressures and temperature in the AT hydraulic system. The instrument consisted of two pressure gauges with 0–2 000 kPa and 0–1 000 kPa measuring ranges and accuracy class 1 and a multimeter with 0–400 °C measuring range and accuracy of ±1 °C. The engine speed was read from the tachometer of the vehicle instrument panel.

The fluid pressures were measured when the vehicle was moving and the ATF temperature was stabilized at 80±2 °C, in the full range of gearbox ratios (in gears from 1 to 4), at engine speeds ranging from 1 000 rpm to 4 500 rpm, with the drive mode selector lever set to "D", pursuant to the automatic transmission testing method having been developed.

1. The diagnostic instrument kit, consisting of measuring pressure gauges and a multimeter, was installed on the dashboard in the vehicle passenger compartment.
2. The measuring pressure gauges were connected by means of flexible hydraulic pipes (5 in Fig. 6) and mechanical adapters to diagnostic take-off points D_1 and D_2 of the ZF-4HP24 automatic transmission.
3. A temperature probe (6 in Fig. 6) of the multimeter (4 in Fig. 6) was installed at the end of the ATF dipstick (the D_T temperature measurement point).
4. The engine was started and the vehicle was driven to travel 30 km in urban traffic conditions for the whole ATF volume in the automatic transmission to reach the prescribed working temperature (of 80±2 °C, according to publications [17, 20]).

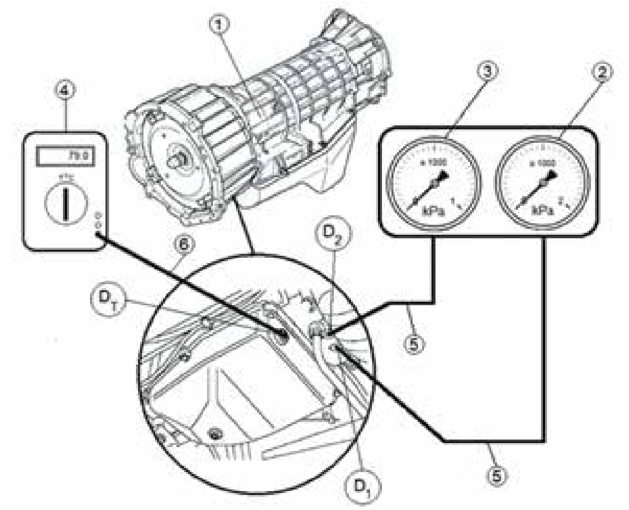


Fig. 5. Schematic diagram of the measuring system: 1 – the ZF-4HP24 automatic transmission; 2 – pressure gauge with 0–2 000 kPa measuring range; 3 – pressure gauge with 0–1 000 kPa measuring range; 4 – all-purpose multimeter; 5 – flexible hydraulic pipes with adapters; 6 – ATF temperature measuring probe with an electrical cable; D_1 – take-off point to measure the main supply pressure p_{D1}; D_2 – take-off point to measure pressure p_{D2} in the torque converter; D_T – take-off point to measure the ATF temperature in the transmission sump

5. When the ATF working temperature in the automatic transmission was stabilized, measurements of the main fluid pressure in the actuator supply line (p_{D1}) and the pressure in the torque converter (p_{D2}) at two diagnostic take-off points of the ZF-4HP24 automatic transmission were started. This was done as follows:

- The vehicle was placed on a straight road section about 3 km long in a closed area.
- The drive mode selector lever was set to "D/1", the vehicle was started to move, and engine speed was set to values from n_s = 1000 rpm to n_s = 4500 rpm in 500 rpm intervals, according to vehicle tachometer readings.
- For each stabilized engine speed, three measurements of the main fluid pressure in the actuator supply line (p_{D1}) and the pressure in the torque converter (p_{D2}) were taken in 10 s time intervals, with checking simultaneously the current ATF working temperature.
- An identical procedure was followed to measure the p_{D1} and p_{D2} pressures in successive gears up to "4".
- Each measurement result was taken as the arithmetic mean of the three pressure values read for a specific engine speed ns and a specific gearbox ratio implemented.

To carry out measurements for gearbox ratios "1" to "3" being implemented, a function of the electronic automatic transmission (EAT) controller was used that makes it possible to eliminate the highest gearbox ratios. When the drive mode selector lever is set to "D/1", only one gearbox ratio can be used. When the lever is shifted to "D/2", the vehicle can be driven in gears "1" and "2". Similarly, for the "D/3" lever position the gears that can be used are "1", "2", and "3" and the shifting of the lever to "D" enables the use of all the four gearbox ratios.

4. Analysis of results of the field tests

Results of measurements of the main fluid pressure in the actuator supply line (p_{D1}) and of the pressure in the torque converter (p_{D2}) in the hydraulic system of the automatic transmission have been presented in Figs. 6, 9, and 12. When analysing the pressure curves obtained, one may notice effects of operation of the proportional valve MV 4, which changes the ATF flow and regulates the pressure in the line that supplies fluid to the hydraulic actuators of the automatic transmission depending on signals coming from the EAT controller [16, 17]. There is no ATF pressure sensor in the hydraulic control system; therefore, the output pressure of the MV 4 valve cannot be regulated in a system of closed loop feedback with the EAT controller. If the hydraulic system is insufficiently effective due to excessive internal ATF leaks between mating parts or because excessive filter flow resistance prevents the hydraulic pump from adequate sucking of the fluid [4], the values of the pressures regulated by the MV 4 valve will be lower than they would be if the hydraulic system were fully efficient. It should be stressed here that the value of the main fluid pressure in the actuator supply line at a specific state of operation of the automatic transmission is chiefly determined by the degree of wear and tear of system components. Variations in the pressure p_{D1} of ATF supply to hydraulic actuators of the automatic transmission vs. the engine speed n_s (the hydraulic pump rotor speed) for gearbox ratios "1" and "2" have been shown in Fig. 6.

With increasing engine speed n_s, the ATF pressure in the hydraulic system grows, regardless of the technical condition of the automatic transmission. The value of the actuator supply pressure p_{D1} is limited by the operation of pressure-regulating valve MV 4. Before the servicing, the actuator supply pressure p_{D1} measured when gear ratio "1" was implemented in the transmission changed from p_{D1} = 610 kPa at an engine speed of n_s = 1000 rpm to p_{D1} = 750 kPa at an engine speed of n_s = 4 500 rpm. After the servicing, the actuator supply pressure p_{D1} for the transmission operating in gear "1" changed from p_{D1} = 700 kPa at an engine speed of n_s = 1000 rpm to p_{D1} = 780 kPa at an engine speed of n_s = 4 500 rpm.

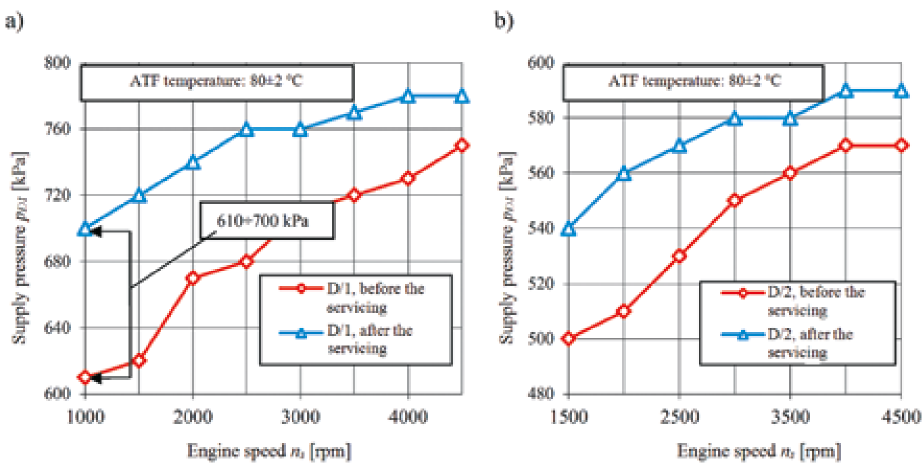


Fig. 6. ATF supply pressures for fresh and used fluid, with drive mode selector switch set to "D": a) – gear "1"; b) – gear "2"

This means that the fluid pressures after the servicing grew by 12.8 % for n_s = 1000 rpm and by 4.29% for n_s = 4 500 rpm, which can be easily explained by higher viscosity of the fresh fluid (after the replacement) and, in consequence, lower hydraulic losses at the "piston-cylinder" pairs in the actuators and between the mating parts in the gear pump. The replacement of the suction filter with a new unit, having lower suction resistance, also results in an increase in the pump delivery rate and in the fluid pressure built in the hydraulic system.

According to data given in the service manual [20], the fluid supply pressure at the idle engine speed (about n_s = 1000 rpm) and with the selector lever set to D/1 should be within a range of p_{D1} = 630–710 kPa. The actuator supply pressure p_{D1} measured before the servicing was lower by 20 kPa than the lower acceptable limit; after the servicing, it was in the upper part of the tolerance range (Fig. 6a). In gear "1", the ATF is supplied to clutches 4 and 11. The driving power is transmitted through epicyclic gearsets, with simultaneous operation of freewheel mechanism 15, to gearbox output shaft 13, according to the schematic diagram shown in Fig. 7.

The curves representing the actuator supply pressures p_{DI} measured for the transmission operating in gears "2" and "3" are similar, in terms of their shape, to those plotted for gear "1", but the pressure values represented by them are lower than those of the latter in the whole range of engine speeds n_s. For the selector lever set to "D" and the transmission operating in gear "2", the actuator supply pressure p_{DI} measured before the servicing changed from p_{DI} = 500 kPa at an engine speed of n_s = 1500 rpm to p_{DI} = 570 kPa at an engine speed of n_s = 4500 rpm.

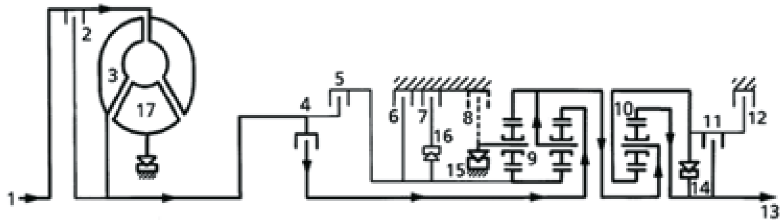


Fig. 7. Schematic diagram of power flow for the transmission operating in gear "1". Drive mode selector lever set to D/1 [17, 20]

After the servicing, the actuator supply pressure p_{DI} for the transmission operating in gear "2" changed from p_{DI} = 540 kPa at an engine speed of n_s = 1500 rpm to p_{DI} = 590 kPa at an engine speed of n_s = 4500 rpm. These pressure values exceeded those recorded before servicing the transmission by 7.4 % at n_s = 1500 rpm and by 3.39 % at n_s = 4500 rpm. In this case, again, the fluid pressure growths can be explained by higher viscosity of the fresh fluid and by lower suction resistance in result of the transmission servicing work.

For gear "2" to be implemented, the ATF is supplied to actuators of clutches 4 and 11 and brakes 6 and 7 (Fig. 8). Freewheel mechanism 15 is overrun (its members can rotate in relation to each other). The sun wheel shaft in gearset 9 is locked. Freewheel mechanisms 14 and 16 are engaged (they rotate as solid units). Epicyclic gearset 10, rotating as a solid unit, transmits power to gearbox output shaft 13.

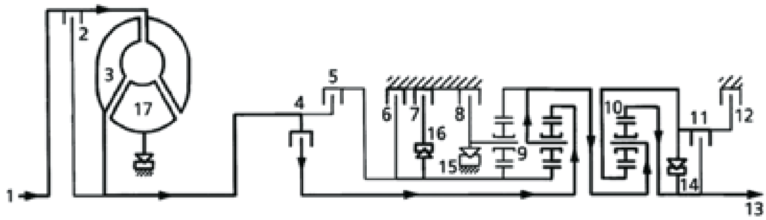


Fig. 8. Schematic diagram of power flow for the transmission operating in gear "2". Drive mode selector lever set to D/2 [17, 20]

It can be seen in the power flow diagrams for the ZF-4HP24 automatic transmission that when gear "1" is implemented in the gearbox (Fig. 7), only two actuators (that engage clutches 4 and 11) are supplied with the ATF. In gear "2", the electrohydraulic controller directs the ATF flow not only to the actuators of clutches 4 and 11 but also to the actuators of brakes 6 and 7. The larger number of the actuators supplied with the fluid translates into a possibility of higher hydraulic leakage rates and, in consequence, bigger drops in the fluid supply pressure at similar settings of pressure-regulating valve MV 4.

When the selector lever was set to "D" and gear "3" was implemented in the gearbox (Fig. 9a), the actuator supply pressure p_{D1} before the servicing changed from p_{D1} = 500 kPa at an engine speed of n_s = 1 500 rpm to p_{D1} = 590 kPa at an engine speed of n_s = 4 500 rpm.

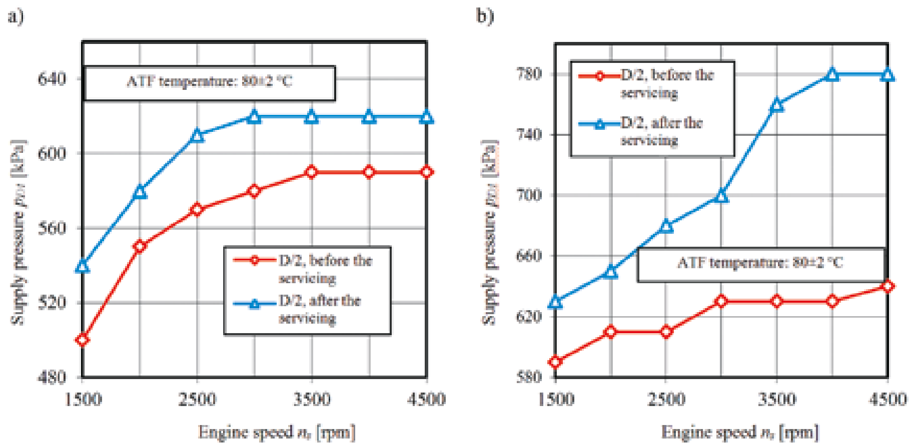


Fig. 9. ATF supply pressures for fresh and used fluid, with drive mode selector switch set to "D": a) – gear "3"; b) – gear "4"

After the servicing, the actuator supply pressure p_{D1} for the transmission operating in gear "3" changed from p_{D1} = 560 kPa at an engine speed of n_s = 1 500 rpm to p_{D1} = 620 kPa at an engine speed of n_s = 4 500 rpm, i.e. these pressure values exceeded the corresponding figures recorded before servicing the transmission by 10.7 % at n_s = 1 500 rpm and by 4.84 % at n_s = 4 500 rpm.

Gear "3" is implemented in the transmission when clutches 4, 5, and 11 and brake 7 are engaged (Fig. 10). Freewheel mechanisms 15 and 16 are overrun. Epicyclic gearset 10 transmits power to gearbox output shaft 13.

When the selector lever was set to "D" and gear "4" was implemented in the gearbox (Fig. 9b), the actuator supply pressure p_{D1} before the servicing changed from p_{D1} = 590 kPa at an engine speed of n_s = 1 500 rpm to p_{D1} = 640 kPa at an engine speed of n_s = 4 500 rpm.

After the servicing, the actuator supply pressure p_{D1} for the transmission operating in gear "4" was p_{D1} = 650 kPa at an engine speed of n_s = 1 500 rpm and p_{D1} = 780 kPa at an engine

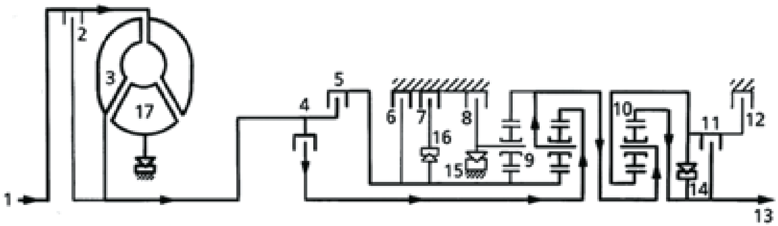


Fig. 10. Schematic diagram of power flow for the transmission operating in gear "3". Drive mode selector lever set to D/3 [17, 20]

speed of n_s = 4500 rpm, i.e. these pressure values exceeded the corresponding figures recorded before servicing the transmission by 9.23% at n_s = 1500 rpm and by 17.9% at n_s = 4500 rpm.

For gear "4" to be implemented, the ATF is supplied to actuators of clutches 4 and 5 and brakes 7 and 12 (Fig. 11). Freewheel mechanisms 14, 15, and 16 are overrun. The sun wheel shaft in gearset 10 is locked. Epicyclic gearset 10 transmits power to gearbox output shaft 13.

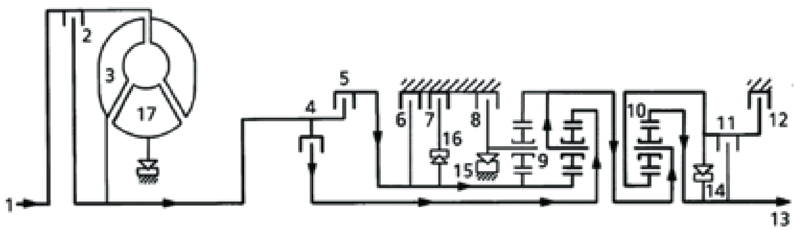


Fig. 11. Schematic diagram of power flow for the transmission operating in gear "4". Drive mode selector lever set to D/4 [17, 20]

Curves representing the ATF pressure p_{D2} in the AT torque converter vs. the engine speed at the drive mode selector lever set to D and at gears "1" and "3" being implemented in the transmission have been shown in Fig. 12. Before the servicing, the fluid pressure p_{D2} in the AT torque converter at the drive mode selector lever set to D and at gear "1" being implemented (Fig. 12a) changed from p_{D2} = 300 kPa at an engine speed of n_s = 1000 rpm to p_{D2} = 660 kPa at an engine speed of n_s = 4500 rpm. After the servicing, the ATF pressure p_{D2} in the torque converter was p_{D2} = 360 kPa at n_s = 1000 rpm and p_{D2} = 660 kPa at n_s = 4500 rpm, i.e. it was higher by 16.7% than the figure recorded before the servicing at n_s = 1000 rpm and it remained unchanged at n_s = 4500 rpm.

The pressure vs. engine speed curves, representing the ATF pressure p_{D2} measured before and after the servicing in the AT torque converter for gear "1" being implemented in the gearbox, are almost identical to each other in terms of their shape. In the engine speed range of n_s = 2000–4500 rpm, the fluid pressure values measured after the servicing only slightly exceeded those measured before the servicing. For the engine speed rising from n_s = 1000 rpm to 1500 rpm, a rapid growth (by more than 100%) was observed in the fluid pressure p_{D2} in the torque converter. When the selector lever was set to "D" and the transmission was operating in gear "3" (Fig. 12b), the ATF pressure p_{D2} measured in the torque converter before the transmission servicing changed from p_{D2} = 430 kPa at an engine speed of n_s = 1000 rpm to p_{D2} = 500 kPa at an engine speed of n_s = 4500 rpm. After the servicing, the ATF pressure p_{D2} in the torque converter at gear "3" being implemented in the transmission grew by 18.8 % for n_s = 1000 rpm and by 5.66 % for n_s = 4500 rpm. The gear ratios are shifted by two-position on-off solenoid valves MV 1 and MV 2.

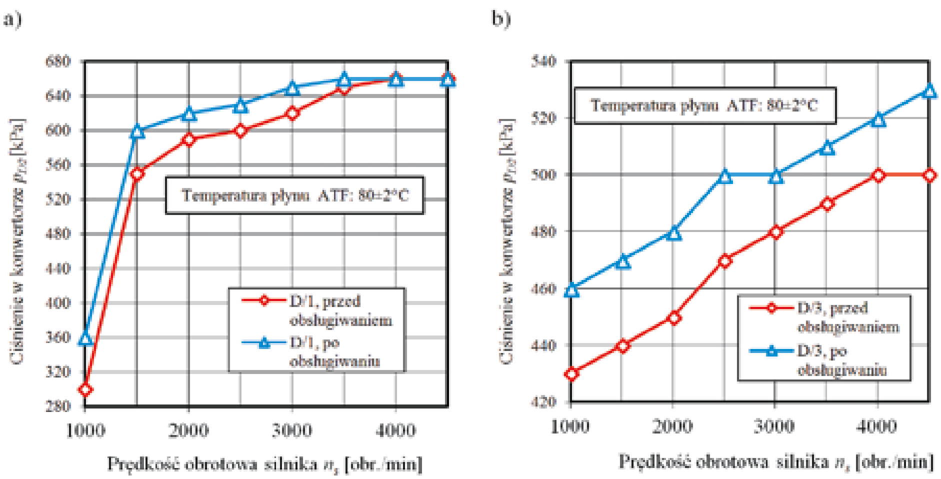


Fig. 12. ATF pressures in the torque converter for fresh and used fluid, with drive mode selector switch set to "D": a) – gear "1"; b) – gear "3"

When p_{D1} pressures were measured in the automatic transmission before the servicing, large pressure fluctuations were observed but they could not be evaluated in quantitative terms because of the measurement method adopted. After the ATF replacement with fresh fluid, the p_{D1} pressure fluctuations considerably decreased. This is an important finding, informing the researchers about the influence of the service work done on the parameters of operation of the AT hydraulic system. It should be remembered that the automatic transmission under tests showed minor malfunctions, manifesting themselves in low gear shift quality (jerks) and noticeable slippage when the vehicle was driven in the conditions of a significant load. The shift process quality assessment is based on the gear shift time, which is defined as the time of slippage of the set of clutches and brakes that implement a specific gear ratio, and on the pressure impulse in the line that supplies fluid to the actuators implementing a specific gear ratio during the gear shift process [1, 2, 15]. It should also be emphasized that the malfunctioning of the AT under tests before the servicing grew worse with increasing temperature of the fluid and AT components, i.e. with decreasing fluid viscosity and pressure in the hydraulic system. The ATF replacement with fresh fluid (having higher kinematic viscosity) and the replacement of the suction filter with a new unit were found to result in an increase in the fluid pressure in the hydraulic actuator supply line in specific AT operation states and in elimination of the transmission malfunctions.

Additionally, kinematic viscosity of the DEXRON IID/III fluid was determined for fluid samples taken from the AT under tests before the servicing (when the vehicle had travelled Sp = 148 345 km in total) and for samples of the fresh fluid used for replacement when the transmission was serviced (Fig. 13).

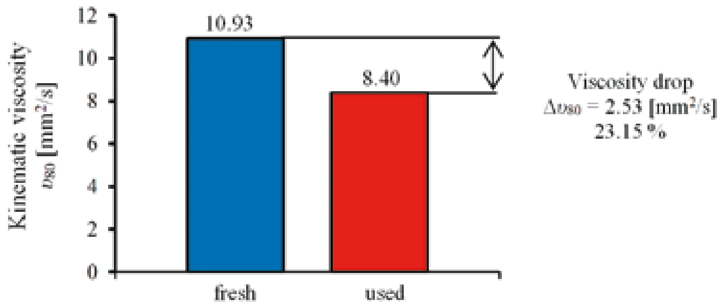


Fig. 13. Kinematic viscosity υ_{80} of ATF DEXRON IID/III samples taken from the transmission of a vehicle that had travelled S_p = 148 345 km in total ("used" fluid) and of fresh ATF ("fresh" fluid)

The ATF viscosity tests were carried out at a temperature of 80 °C corresponding to the normal working temperature of the AT under tests. Pursuant to Polish Standard PN-EN ISO 3104:2004, the ATF viscosity shall be determined at temperatures of 40 °C and 100 °C [14]. In authors' opinion, however, the measurements of fluid viscosity at a temperature of 80 °C could help to identify the reasons for malfunctions of the automatic transmission under tests.

The drop in viscosity of the DEXRON IID/III fluid samples taken from the automatic transmission under tests in comparison with the viscosity of fresh automatic transmission fluid (ATF), determined at a temperature of 80 °C, was $\Delta\upsilon_{80}$ = 23.15 %. The drop in viscosity of used ATF (in relation to fresh fluid viscosity) was on a level similar to that of a fluid sample taken from a conventional AT having travelled about 100 000 km, experimentally tested at temperatures of 40 °C ($\Delta\upsilon_{40}$ = 24.49 %) and 100 °C ($\Delta\upsilon_{100}$ = 19.95 %) [3].

5. Recapitulation

The results obtained from tests of ATF pressures at diagnostic take-off points of the hydraulic system of a ZF-4HP24 automatic transmission have shown that changes in the working characteristics of the automatic transmission fluid and in the technical condition of the suction filter (flow resistance) may have an impact on the functioning of an automatic transmission that was in service for a long time (in a vehicle that travelled about 150 000 km). The diagnostic instrument kit used for the experimental field tests did not offer a possibility of qualitative assessment of the operation of an automatic transmission, including the shift process quality and size of fluctuations of the fluid supply pressure. For such an assessment to be carried out, time histories of the pressures of fluid supplied to hydraulic actuators should be recorded during a road test. The records obtained would make it possible to determine the time of specific gear shift processes and the nature of the ATF pressure vs. time curves [1, 2, 9, 15]. A drop in the ATF pressure in the hydraulic system of an automatic transmission in specific vehicle movement conditions will result in a proportional decrease in the force exerted by the actuator on a multidisc brake or clutch to implement the selected gear ratio and this is connected with excessive brake or clutch slippage. The excessive slippage, in turn, will cause "burning" and "flaking" of friction clutch linings made from cellulose or aramid fibre, or even welding of such materials [18, 19]. With increasing slippage, the ATF temperature locally rises in the friction zone, causing excessive oxidation of the fluid; moreover, high relative velocities between friction surfaces intensify the ATF shearing process [19]. Changes in the physical and chemical ATF properties result in malfunctioning of the hydraulic system. The malfunctioning, in turn, leads to deterioration in the physical and chemical properties of the ATF. The malfunctioning of the automatic transmission under tests before the servicing grew worse with increasing fluid temperature, i.e. with decreasing fluid viscosity. This may be connected with significant wear and tear of AT components, which resulted in excessive internal leaks in the part supplied with ATF under the main pressure generated in the hydraulic system. Replacement of the ATF with fresh fluid, whose kinematic viscosity at the working temperature is higher than that of the fluid after a long period of being in service (by more than 20 %) results in so big a reduction in hydraulic leaks at the "piston-cylinder" pairs in the actuators that adequate functioning of the AM hydraulic system can thus be restored in spite of significant wear and tear of AT components.

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