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Progress in a pressure controlled chain converter hydraulics

A high potential to increase the overall efficiency of a chain converter transmission is by optimizing the clamping and ratio hydraulics. A new pressure controlled system was developed, which controls the oil pressure and volume flow on demand. This leads to a significant reduction of the required hydraulic energy, whereby a chain converter transmission is able to compete against hydrostatic-powersplit tractor drive trains in terms of efficiency. Further energy savings were realized by reducing the clamping forces closer to clamping force requirements.

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Stepless tractor drive trains were able to establish in sophisticated markets since the introduction in 1996. In the meantime the tractor companies Fendt, Case/Steyr, John Deere and Deutz-Fahr offer tractors with hydrostatic-powersplit transmission [1], lately Massey Ferguson presented a new series including the Fendt Vario-transmission [2]. Due to higher comfort and improved efficiency there is a lively discussion about stepless transmissions in small and medium engine power range, where hydrostatic-powersplit transmissions are not offered at the moment. In this segment there is a high cost pressure and also no expectation to get a high tech tractor by the customer. Thus chain converters in a simple transmission structure could offer a continuously variable drive train, especially because they feature an outstanding mechanical efficiency [3]. Also the transmittable power is growing since this technology is used in automobiles [4]. Based on a project of the Collaborative Research Centre 365 sponsored by The Deutsche Forschungsgemeinschaft (German Research Foundation) new concepts for the hydraulics of a chain converter are investigated at the Institute of Agricultural Machinery at Technische Universität München in order to increase the overall efficiency of such a transmission [5].

Pressure controlled clamping hydraulics

The ratio adjustment is realized by hydraulics. In addition a clamping force is required, because the power is transmitted by a chain just through friction. If the clamping force is not sufficient, the chain starts to slip and could lead to a damage of the CVT [3]. The amount of this hydraulic clamping pressure is mainly addicted to the actual torque. Further parameters affecting the need of clamping pressure are actual ratio and speed of input resp. output shaft.

Today's in series produced chain converter transmissions (e.g. Audi Multitronic [4]) generate the clamping pressure by a torque proportional throttling of a constant oil flow inside the so called hydraulic torque sensors. Since this high oil flow is necessary for the functionality of the converter only for short time slices, a new pressure controlled energy efficient system was created [5]. The advantages of the constant flow system like high dynamics and fast ratio adjustment without turning shafts could be retained. Oil pressure inside the clamping cylinders is now electronically controlled by a variable displacement pump and a pressure control valve for each shaft according to the actual torque which is measured at the new torque sensors. According to the well known PIV-constant flow-system the new torque sensors still include the so called „pump function“. This feature increases pressure up to the torque proportional value purely mechanically and with high dynamics. This happens if pressure is too low due to inertia of valves or pump. Because of this pump function the transmission can be operated safely almost without over clamping which is realized by higher oil pressure and is essential part in most published concepts of pressure controlled systems. The over clamping causes problems like increasing pump capacity (higher system pressure and leakage) and higher mechanical losses.

Pressure and oil flow on demand

A high potential to save energy is given by the supply of pressure and oil flow on demand. As shown in [6] only a low oil flow is needed for increasing pressure, if design has been done carefully in the face of leakage. Whilst change of ratio a much higher oil flow is required depending on the rate of ratio change. Therefore the possible energy saving is affected by frequency of ratio change. To keep it low it is recommended to tolerate a certain decrease of engine speed, before the transmission controller changes ratio.

Optimized clamping pressure

As already mentioned pressure inside the clamping cylinder consists of two parts: One ensures the transmission of power via friction, the other is needed for adjustment of ratio. To get a constant ratio a certain ζ-ratio

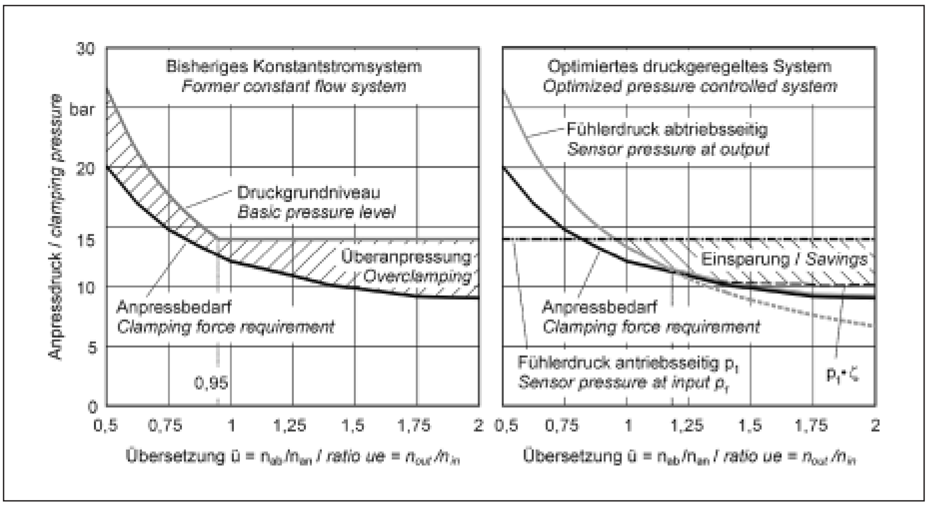

Fig. 1: Basic clamping pressures shown over ratio used for constant flow resp. pressure controlled clamping system, input torque 140 Nm, input shaft speed 1000 rpm, mechanical efficiency 95%

must be kept, to vary ratio it must be changed. ζ represents the quotient of the clamping forces at in- and output shaft at steady state [3].

These two pressure parts can also be found at the well-known PIV system including two hydraulic torque sensors. There the necessary pressure to get a no-slip transmission is produced by throttling the constant oil flow. Because both torque sensors (equal sensor constant c_F = 10 Nm/bar) are connected in series and thereby the higher pressure dominates, the higher torque of in- and output shaft dominates and represents the basic pressure level (*fig. 1*). The amount of torque at both shafts is equal when speed ratio n_{out}/n_{in} corresponds to mechanical efficiency μ_{mech} of the chain converter. In addition the ratio controller increases just one pressure to reach the target ratio. Thus both pressures conform the ζ-ratio which is characteristic for the actual operating point. Indeed this ζ-value describes only the ratio of the clamping forces and because of equal areas at the cylinders more or less the ratio of the clamping pressures. In doing so, the absolute values of numerator and denominator are not defined.

The clamping force requirement of the output shaft is the main factor for dimensioning a clamping system. *Figure 1* shows the clamping force requirement for the used size of chain converter which was measured by [3] according to the ζ_{max}-method (safety against slip 1,1-1,2). Additionally both torque-proportional pressures „sensor pressure at input" and „sensor pressure at output" are plotted (pressure controlled system, sensor constant c_F = 10 Nm/bar). If pressure falls under these values the torque sensors try to increase pressure by using the pump function. This happens because the slope of the ball ramp is constant where a torque-proportional axial force is generated. These axial forces multiplied with the area of the sensors results in the shown sensor pressures. With the new pressure controlled clamping system it is possible to adjust clamping pressure independently at each shaft. Thus „sensor pressure at input" and „sensor pressure at output" can be used as basic pressure for the respective shaft up to a ratio at which „sensor pressure at output" falls below the value of clamping force requirement (in figure 1 at about ü = 1,2). According to the constant flow system the ratio controller increases one of the two pressures to reach target ratio.

Potentials of energy savings

At ratio ü = 1/i > μ_{mech} energy savings result by using the optimized clamping pressure, because then ζ is always higher than 1. This means the required clamping pressure at input shaft must be higher than the one at output shaft. Anyway it is already due to the different basic pressures. For ratio ü < μ_{mech} and conditions, where ζ is smaller than 1, it can be sufficient to increase „sensor pressure at input" by the ratio controller and to keep „sensor pressure at output" as the higher pressure. In opposition to this behavior in the constant flow system the higher sensor pressure will set the basic pressure level for both shafts and is increased at one shaft by the ratio controller. This results in a higher pressure level.

For a precise evaluation of the energy consumption of the new pressure controlled clamping system the hydraulic power (without efficiency of the pump) is compared to the one of a already optimized constant flow system which is operated at an oil flow of 6 l/min. This value permits a speed of change of ratio which is high enough for a satisfying operation. For comparison purposes, the strategy of the constant flow clamping controller as well as the described optimized calculation of the clamping pressure is used to assess the further energy saving. The following results were acquired by simulation, but have been proved by measurements at the test rig using the pressure controlled system including the constant flow clamping strategy. For the tests a cycle was created which includes changes of ratio with different speed of change at 50% of time. By using the pressure controlled clamping system including the constant flow logic 80% of the hydraulic power is saved. The optimized clamping controller enables a further increase in savings of up to 83% of the hydraulic power of the former constant flow system. If the hydraulic power is related to the mechanical one, the former constant flow system has P_{hyd}/P_{mech} = 1,47%, whereas the pressure controlled system consumes a value of 0,31% (including constant flow logic) resp. 0,25% (optimized clamping pressure controller) of the mechanical power. Moreover an increase of mechanical efficiency is expected due to the lower level of pressure and the resulting clamping forces.

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