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Pulley adjustment systems and gearing control for continuously variable pulley transmissions

New concepts for the design of hydraulic pulley adjustment systems for continuously variable pulley transmissions have been developed. The aims include an improvement and extension of the function and a securing of sufficient adjustment power for the high demands in tractors.

First of all, a functionally extended and improved constant-flow adjusting system adapted for the marginal conditions in modern tractors is introduced and this is followed by the presentation of first results from a new energy-saving hydraulic system with pressure control.

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The introduction of continuously variable transmissions in the serial production of standard tractors (Fendt Vario) and system vehicles (Claas Xerion) has begun [1]. Both transmissions are based on hydrostatic power splitting concepts with maximum efficiency (without axles) of something over 90% [2]. A cost-efficient technology for step4less transmissions is also represented by the continuously variable pulley transmissions from P.I.V. Reimers (chain converter) and Van Doorne Transmissie (VDT, thrust joint band). These transmissions work through frictional power transference. Their strengths (high total degree of efficiency even without power splitting) are , according to [3], relevant for tractors in the lower up to medium power class.

Clever design of the hydraulic system for pulley adjustment pressure and conversion setting allows for the best possible use of the extraordinarily high efficiency potential (the mechanical efficiency indicates maximum values of 95%). Above all, over-adjustment must be avoided [4] and the energy consumption of the supply hydraulics optimised [5]. Within the concept of the special research sector 365 „Environmentally-friendly drive technology for vehicles" an improvement of the chain converter hydraulics has been worked on at the Technical University of Munich since 1993. In order to achieve a high longevity when applied in tractors the adjustment system must be in the position to always have a satisfactory amount of clamping power on offer. This must apply even with the hardest torque strains so that slipping of the transmission with subsequent damage to the chain converter can be avoided.

Modified constant-flow hydraulics

The P.I.V. constant flow system [4], with its secure thrust pressure adjustment (torque sensor) represented the hydraulic basis for the first generation of continuously variable pulley transmissions in tractors. In order to adjust this in line with the rapidly growing numbers of hydraulic drive applications (CAN-BUS) a system was developed that allowed for a substantially more flexible electronic control of power transference conversion with rpm measurements, *fig. 1*. Here two further control valves are integrated with the help of which an adjustment in the starting conversion can be carried out within less than 2 s even where the chain converter is not active. The control valve used , based on C-167 [6] is increasingly used in agricultural machinery. The hydraulic supply takes place either cost-efficiently out of the tractor hydraulic system, or with the help of a separate (60 bar, around 10 l/min) pump [7]. The hydraulically piloted ratio control valve fitted with its own regulating circuit was developed by the author [8]. Through a specific positioning of the pressure difference valve, the ratio-changing time of the chain converter could be considerably reduced. For mo-

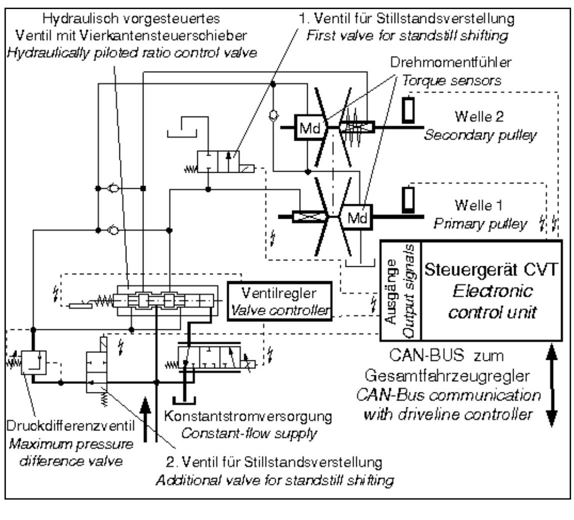
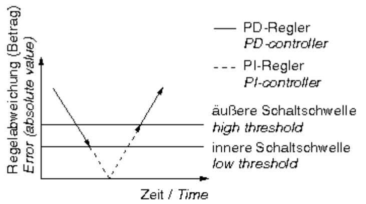


Fig. 1: A modified concept for a constant-flow pulley adjustment system

- Kettenwandler mit Anpress-System: I-Strecke
  Chain converter with clamping system: Integral plant
- Variante 1: PD-Regler
  Configuration 1: PD-Controller
- Variante 2: PD/PI-Regler mit Strukturumschaltung
  Configuration 2: PD/PI-controller (structure switching)



Vergleich zwischen den Lastfällen M_{ab} = 100 Nm und M_{ab} = 0 Nm *Comparison between the loads M_{ab} = 100 Nm und M_{ab} = 0 Nm*	relative bleibende Regelabweichung *relative steady-state error signal*	
$ü = n_{ab}/n_{an}$	PD	PD/PI
0,5	-1,3 %	0,0 %
1,0	-1,1 %	0,0 %
1,5	-0,9 %	0,1 %
2,0	-0,8 %	0,2 %

Abtriebsseitiges Massenträgheitsmoment = 1 kgm², n_{an} = 1000 min⁻¹, Q = 10 l/min, Öltemperatur = 80°C
Inertia torque on output end = 1kgm², input speed n_{an} = 1000 min⁻¹, flow Q = 10 l/min, oil temperature = 80°C

Fig. 2: Suitable structure of ratio control minimises load-dependant steady-state error

ving through the complete transmission range only 1.3 s was required. The conversion controller has the task of keeping the remaining signal errors as small as possible in the presence of higher conversion dynamics and of minimising the influence of interference factors such as the differing of draught resistance in fieldwork or tension forces during gear changes in split power transmissions (*fig. 2*). In that the chain converter shows I-behaviour because of the ring-formed adjustment cylinder, a simpler structure-variable controller is applied which reduces large conversion deviations through a PD structure and small ones through a PI structure [9]. A hysteresis during ratio changing resists pendulating between both controls. Measurements confirm the unsusceptability of this control structure to damage during disturbing load changes. It could be proved in trials that the conversion control works dependably even with oil temperatures of -18 °C.

Pressure-controlled hydraulic system

As publicised earlier [10], a pressure controlled hydraulic system with adjustable pump theoretically offers the least-possible energy consumption in that pressure and volume flow is matched to actual requirements. New simulation calculations with more sophisticated models in the establishment of test drives (field and transport work) with the Munich research tractor [11] confirmed the large energy saving potential. In total it was shown that using a pressure-controlled pulley adjustment system compared with an optimised constant flow system meant that considerable energy savings could once again be achieved. The proportion of hydraulic energy in total energy produced (via internal combustion engine) reduces from around 1.7% to 2.5% to 0.4% to 0.6% (according to the tractor operation) and indicates that an increase in the total efficiency of the chain converter of an average of around one percentage point is to be expected.

As already mentioned, the hydraulic system must be capable of following even the steepest torque rises with the adjustment pressure control. In the agricultural engineering faculty a new torque sensor has therefore been developed that carries out this function together with the new pressure control [8]. The hydraulic layout could be very easily followed in this case (*fig. 3*).

In a normal situation the pressure on the pulley adjustment cylinders would be adjusted over the pressure regulation valve according to the desired conversion ratio and the torque in force (according to electronic measurement). The system pressure produced by the pump lies in this case only a little higher. The lower threshold presents in this context the necessary minimum pressure for the adjustment of the vane pump. Should the torque rise very quickly, it is not possible for the pressure regulation circuit to react in time because of the delay (almost entirely caused by the valves) of up to 100 ms. In this case, the pump effect of the new torque sensor applies, and the pressure rises immediately.

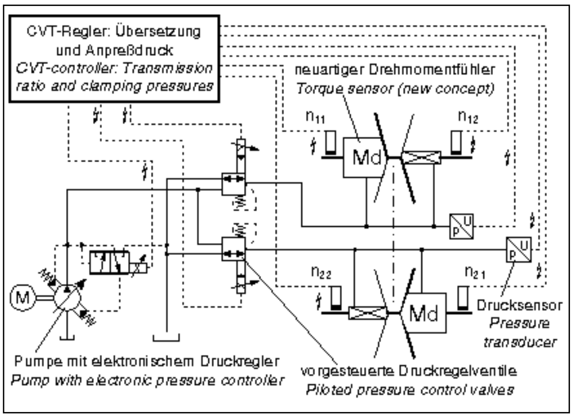


Fig. 3: New concept for CVT hydraulic with pressure control

In test station trials the complementary working of pressure control valve and torque sensor could in the meantime be demonstrated (fig. 4). Through the pumping action, the pulley adjustment pressure is raised to 10 bar without delay from the beginning of the torque rise. Then there's a delay of around 40 ms before the new reference value is established by the pressure regulation valve.

Further advances

The next moves must involve the final developments and investigation of strategies for pressure regulation (supported by the application of dynamic simulations with MATLAB/SIMULINK). In this context, fig. 4 shows a first comparison between measurement and simulation. The next step should be the integration of the thus-validated models for pressure regulation valve and torque sensor within the simulation of the complete pressure regulated hydraulic system with everything brought together within the already existing model of the complete chain conversion test station [12]. The final development of the regulating strategies and of the new hydraulics should, finally, be supported experimentally in actual transmissions.

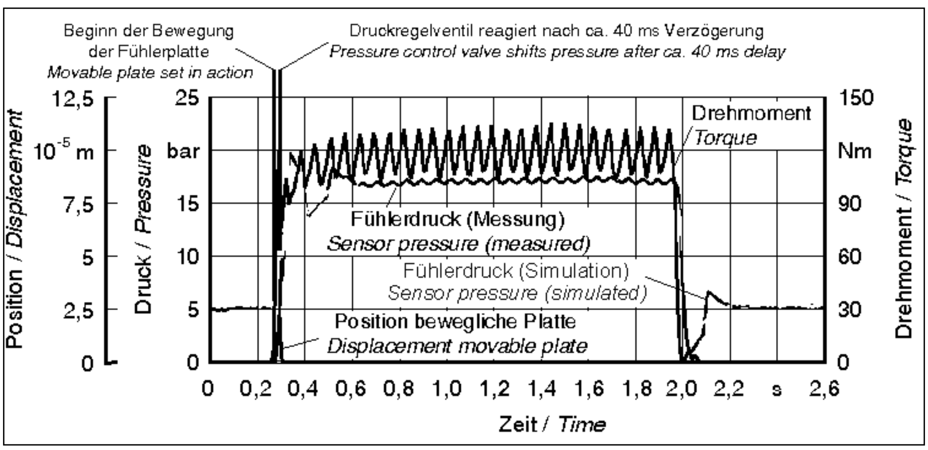


Fig. 4: "Pumping function": compensation for the time delay in the pressure control loop

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