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Control of Continuously Variable Chain Converters in Transmission Systems

Continuously variable transmissions (CVT) are constantly gaining in importance in mobile machines as well as in passenger cars. Special types of CVT are PIV-based pull type chain converters. New applications are raising the requirements for controlling these gearboxes. The most important control variable is the speed ratio and the rate of ratio change (di/dt).

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Literature

Literature references can be called up under LT 03613 via internet http://www.landwirtschaftsverlag.com/landtech/local/literatur.htm.

The pull type chain variator has been subject of research projects at the Department of Agricultural Machinery of Technische Universität München for tractors [1] and passenger cars before. In 2002 the results of a mutual large research project of several TUM-departments, sponsored by the DFG („Deutsche Forschungsgemeinschaft") have been presented with the „Autarkic Hybrid" [2]: A parallel hybrid concept passenger car, based on a standard Opel Astra Caravan with Diesel engine, which was equipped with additional components such as an electric engine (120 V, 4 quadrants) and a specially developed chain CVT gearbox with wide spreading in i^2-design. This paper presents the control structure chosen at the Department of Agricultural Machinery to control the speed ratio of the gearbox as well as it's further development for universal use, e.g. for tractor applications.

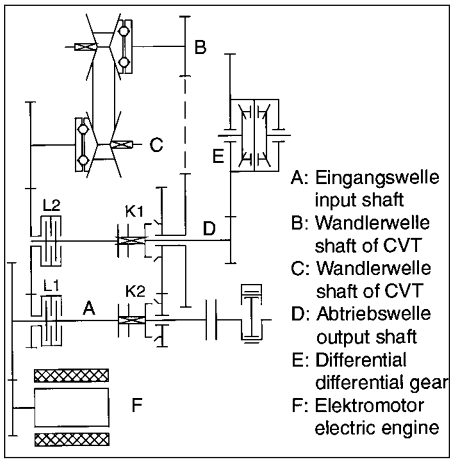

Fig. 1: Structure of the gearbox of Autarkic Hybrid with PIV chain CVT

Structure of the gearbox of Autarkic Hybrid

Figure 1 shows the structure of the gearbox of Autarkic Hybrid. The gearbox is characterised by two driving ranges. In first range (V1) the clutch L1 is closed and variator shaft C is driven by the engine(s). The synchronised collar coupling K1 is also closed and shaft B of the CVT is connected to the final drive (E). In overdrive of range V1 at a speed ratio of approximately i = 0,458, the rotational speed difference in all four clutches disappears and the so-called synchronous point is reached. At this point the second synchronised collar coupling (K2) is being closed and the first wet clutch (L1) can be opened. In that situation (SYN), power still can be transmitted, now without the chain variator being engaged. Since the gearbox has a fixed gear ratio at SYN, acceleration is possible only by rising the engine speed. Further acceleration leads to an operation in second range: By closing the clutch L2, while opening the clutch K1, the driving and driven pulleys are inverted, compared to first range, and second range (V2) is reached, starting in underdrive again. Thus an overall spreading of the gearbox of about 22.5 is realised.

Speed ratio control for range shifts in Autarkic Hybrid

In order to provide fast, comfortable and successful range shifts, it is essential to exactly control the speed ratio at the synchronous point. This is done by controlling the clamping pressures. When controlling the speed ratio at steady state, on one hand, the clamping forces need to be high enough to prevent damage by slip of the chain, on the other hand a certain ratio of clamping forces has to be achieved, the so called ζ-ratio (ratio of clamping forces between driving and driven pulley) [3]. In standard PIV-clamping system the base level of clamping pressure in the pulleys that prevents the chain from slipping is automatically achieved by throttling a constant oil flow in the so called torque sensors. An additional valve is used to raise one of the clamping pressures by further throttling in order to reach the required ζ-ratio in steady state. The required ζ-ratio is dependent on transmitted torque and speed ratio. Moreover the actual pulley speed leads to centrifugal forces affecting the chain and clamping forces (rotating hydraulic cylinders), so it can be seen as another disturbance variable. Assuming a rather narrow speed range in normal operation when doing

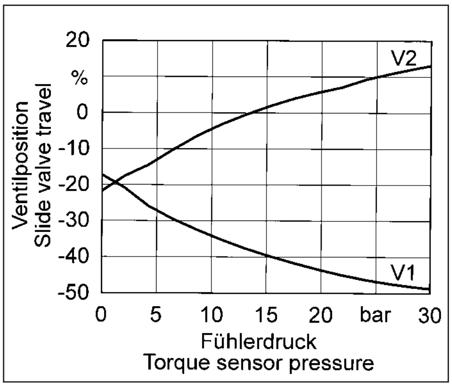

Fig. 2: Manipulated variable versus torque pressure

range shifts and a fixed speed ratio (SYN), the remaining disturbance variable still is torque. Since the variator is changing between engaged an disengaged mode during range shifts, there are extremely high torque gradients. Consequently a range shift leads to changing ζ-ratios during shifting process and thus difference in speed ratio that prevents from successfully completing or at least delays the range shift, because the standard speed ratio controller (closed loop) can only react on actual differences in speed ratio and needs a certain time to compensate any deviation.

Therefore the control was further expanded to represent a disturbance feedforward control. Since the information about current input torque is available by measuring the pressure of the torque sensors (two sensors in series), and the manipulated variable is the position of the actuator („VSS"-valve), which sets a difference in clamping pressures, the influence of torque was mapped in a characteristic curve which has the pressure of the input torque sensor as input and the position of the valve as output (*Fig. 2*). This was also done to minimise the required calculation steps for the disturbance feedforward controller and allow short clock cycles with typical microcontroller hardware (16 bit, 20 MHz). The shown characteristic curves apply for positive traction torque. In incentive operation the curve of the reverse driving range applies. Finally the influence of speed on the required valve position was investigated and also integrated into the controller layout. The taken measures resulted in a significant improvement of quality and reliability of range shifts.

Expanded Control Layout for Universal Chain Variator Applications

When controlling the speed ratio not only in one single point, but over the whole range of spreading, a controller, variable in structure, has proved itself in different CVT applications: By using different sets of parameters, depending on the size of system deviation, a stable system behaviour can be realised though using integral type sets of parameters to avoid a steady state-error signal. Switching between sets of parameters is done by means of hysterisis. Moreover parameters can be found more easily, because only the appropriate partition of operating range has to be observed. By resetting any stored deviation values and the manipulated variable to predefined values, when reaching the given or even additional error signal limits, a very smooth system behaviour without overshooting and hunting (improved ride comfort) can be achieved. *Figure 3* shows the gradient of the speed ratio of a tractor with chain converter type of transmission in trailer operation and software emulated stepped gear mode with and without reset of the controller in other respects using the same control parameters. In road trial an overshoot was felt to be very displeasing especially when downshifting. In the next step of development, the control structure was also expanded by disturbance feedforward, using a RCP-system running under Matlab/Simulink®, now also taking into account the speed ratio. To achieve more flexibility when using different clamping systems, the disturbance variables now are reduced to their origin: Clamping forces are used instead of valve positions or pressures.

The most important non-linearity is the ζ-value for the steady state operation. It was mapped in a characteristic diagram. The minimum clamping force, which is given by the clamping strategy, in conjunction with the ζ-ratio, is used to calculate the other, higher clamping force. With both given clamping forces the required clamping pressures can be calculated and the output can be set, taking into account the influence of speed (centrifugal forces) and the characteristics of the respective clamping system (e.g. characteristic curve of the valve). The controller compensates any further deviation from the desired speed ratio by raising one of the given pressures.

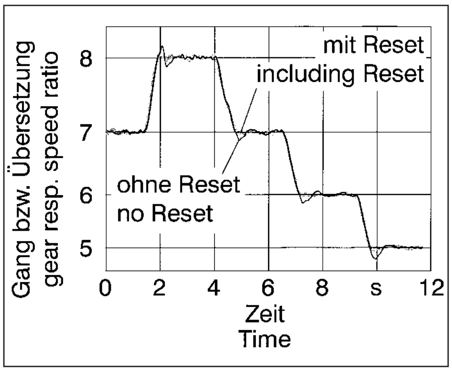

Fig. 3: Influence of resetting the controller

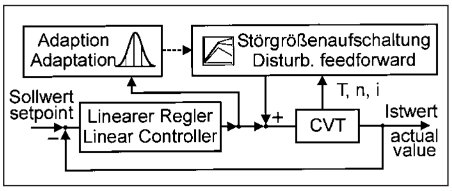

Fig. 4: Simplified structure of the ratio controller

The controller is acquiring the ζ-map of the respective chain converter adaptively during normal operation. The criterion for adaptation is the output of the linear ratio controller, which is supposed to be leading to zero in steady state (*Fig. 4*). Otherwise the map is being fitted to minimise the output of the control. Since the map is made up of several sampling points, weighting functions are used to decide which sampling points are to be fitted an how much. In order to minimise the required computing power, different types of weighting functions for the adaptation process besides the conventional gauss error distribution curve were investigated.

The control design can easily be fitted to different gearbox designs and clamping strategies. Both the conventional clamping system for the well known PIV-based chain converter and a newly developed pressure controlled clamping system [4] were taken into account. In first step a base level of pressure was assumed for the pressure controlled system, which is proportional to the higher torque of both pulleys (according to the conventional system with two sensors). Further optimisation is possible by approaching the actual clamping force requirements [5].

The use of gathered ζ-curves by the new controller layout leads to better performance in ratio-based control strategies. For some applications it might be more useful to control the rate of ratio change [6], which becomes possible by a simple modification: Instead of closed loop controlling the speed ratio, an open loop control uses the proportional behaviour between rate of speed ratio change and the difference between actual clamping forces and steady state clamping forces. Since the steady state forces are known from the ζ-curves this difference can easily be used to compute the required clamping pressures according to the desired rate of speed ratio change.