A COMPUTER CONTROLLED TEST SETUP FOR CONTINUOUSLY VARIABLE TRANSMISSIONS.

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A continuously variable transmission is a complicated system to model and to control. We present a test setup which helps the researchers to model the CVT more accurately and to test the designed controllers. The designed test setup consists of a prototype electronically driven CVT, a 22 kW induction motor with a vector controller, an oil cooling device and instrumentation hardware (sensors, filters and amplifiers). Three programs with user friendly graphical user interfaces are designed for the measurement and control computer. Two programs are developed for open loop experiments; one to measure the static characteristics of the CVT, another to measure the dynamics. The third program is written to test the designed controllers in a very flexible way.

INTRODUCTION

Continuously Variable Transmissions (CVTs) are complex systems, hard to model and to control. Physical modeling is done with the aid of bond graphs. To calibrate these models and to evaluate the quality of these models, experiments are required. Since the behavior of the CVT varies with the engine speed and the oil temperature, it is necessary that we are able to control both, if we want to study these influences. Therefore, we've build a test setup where the engine speed and the oil temperature can be controlled and all the interesting physical variables can be measured.
Once the models are calibrated, they are used for control design. These controllers must anticipate for setpoint variations (tracking), for parameters variations (robustness) and for noise (rejection). The final performance of the closed loop system can be analyzed via computer simulations. If the simulations are promising, an intensive test program is done on the real CVT.
The organization of this paper is as follows: the first section explains the

hardware setup. The second section describes the software that is developed. Finally, we show some results that are obtained with the aid of the test setup.

DESCRIPTION OF THE HARDWARE

The CVT

A Continuously Variable Transmission can be considered as a gear box with an infinite number of transmission ratios. Basically, the system consists of two sets of conical pulley sheaves, with a metal belt in between. This belt can move continuously on the pulleys; it can easily be seen that every belt position corresponds to a new transmission ratio. We refer to [Vanvuchelen-1993/1] for a detailed threatment of CVT's.

The engine

The test setup is powered by an induction motor of 22 kW with a maximum speed of 6000 rpm. The inverter is a Siemens Simovert 3560 of 63 kVA. The inverter is based on the vector control principle, which can be shown to be optimal for induction motors. Since it also allows to control very accurately the speed of the motor or the produced torque, it can be used to give the motor a torque-speed characteristic similar to that of a combustion engine. The idea is then to measure the momentary speed of the motor and send a torque signal to the vector controlled inverter based on the speed torque characteristic of the simulated combustion engine. Communication with the control unit of the test-setup is possible via analog signals, RS-232 or Profibus. We prefer to use electric motors instead of combustion engines because they have no exhaust (laboratory) and the speed (and torque) of an electric motor can be controlled very accuratly (static and dynamic).

The Load

In this test setup there is no load to the CVT, because the behavior of the hydraulic system in the CVT is independent of the load. If the CVT must be tested under load conditions it is best to build it into a car. Simulation of the load of a car with electric motors is difficult and expensive. The energy received from the motor and the CVT must be send back to the electricity supply or send to a resistor network. The motor which simulates the load must have a large speed and torque range.

The cooling unit for oil temperature control

Since the static and dynamic behavior of the hydraulic system depends on the oil temperature, it would be very useful if the temperature of the ATF oil (automatic transmission fuel) could be controlled. To do so, a cooling unit is installed. It consists of a water tank with a radiator. The oil temperature at the input and output of the radiator are measured. The control input of this unit is the water level in the tank. Because there is a continuous feeding and carry off of water, the temperature of the water in the tank remains almost constant. By controlling the inflow of water, we control the water level and thus the cooling capacity of the radiator.

Signal conditioning and interfacing equipment

Collecting CVT-data The signals are measured using a simultaneous sample-and-hold block and a PC data acquisition card. In our case, 15 signals are measured:

- Three speed signals (motor, primary, secondary)
- Three output pressures
- Three servo pressures
- Two temperatures (before and after the cooling unit)
- The water level of the cooling system
- The three signals send to the valve body of the CVT (testing the hardware)

First, all signals are measured using specific sensors. The rotation speeds of the pulleys of the CVT (primary and secondary speed) are measured using wide frequency band inductance based sensors. Toothed wheels, connected to one of the pulley sheaves, generate pulses in the speed sensors. As pressure sensors, strain gauges based pressure sensors with a large bandwidth (response time ¡ 1ms) are used. Special miniature sensors are used to measure the pressures in the valve body. Thermocouple (type k) devices are used to measure the temperatures.
Next, all the measured signals are send to panel displays. These panel displays serve also as the power supplies for the sensors. Further, they generate analog signals ($\pm 10V$) which are proportional to the measured quantity. It are these signals that are send to the acquisition unit. Note that the motor speed is measured with the aid of the vector controller: since the rotor speed is already measured for feedback purposes of the vector controller, it can easily be send to the main control unit. The motor speed signal is send from the interfaces boards on the inverter to the I/O card as an analog signal ($\pm 10V$).
Finally, all signals are filtered with anti-aliasing filters (switched capacitor sixth order Butterworth filters (MF6-50)). The cutoff frequency for the six pressure signal filters can be altered between 31 and 2500 Hz (8 intermediate frequencies). This option is added because the sampling rate differs with the test purposes: measurements for modeling are done at 500 Hz, while control

is done at 61 Hz or 122 Hz. The other cut off frequencies are fixed (temperature signal: 1 Hz, speed signals: 25 Hz).

Generation of steering signals for the CVT The outputs of the control unit are generated with a PC output card. In principle, the test setup has 5 inputs:

- Three duty cycle signals (one for each servo valve)
- The motor speed set point
- The voltage for the hydraulic valve of the cooling system

The inputs of the PWM valves are current signals. A block wave of 61 Hz (or 122 Hz) with variable duty cycle needs to be generated. An extra current pulse at the beginning of each positive step of the block wave must be superimposed, to remove the influence of friction in the PWM servo valves. These current signals are generated as follows: the computer sends signals (with amplitude proportional to duty cycle) to a circuit that generates voltage block waves at 61 Hz (or 122 Hz) with variable duty cycle. Commercial waveform generating IC's where tested but the resulting systems were highly non-linear. A own electronic system was designed which is linear and very accurate.

These voltage signals are then send to a solenoid controller and a current amplifier. The solenoid controller adds an extra current peak at the beginning of the pulse to deal with the friction of the ball in the PWM valve. These signals are send to the PWM valve. An example of the generated signals is given in figure 1.
The motor speed set point is an analog signal that is send to the analog inputs of the vector controller. The voltage for the hydraulic valve of the cooling system is also an analog signal.

The control unit

The control unit is a 486/DX50 PC with the 2 previously mentioned acquisition cards and a 16 channel simultaneous sample-and-hold extension module. A schematic outline of the test set-up is shown on figure 2. Figure 3 shows a photograph of the complete test setup.

DESCRIPTION OF THE SOFTWARE

This section explains the programs that are developed for the test setup. Three different types of applications are developed. First two programs for modeling purposes are presented, next, a program for real time control is explained.

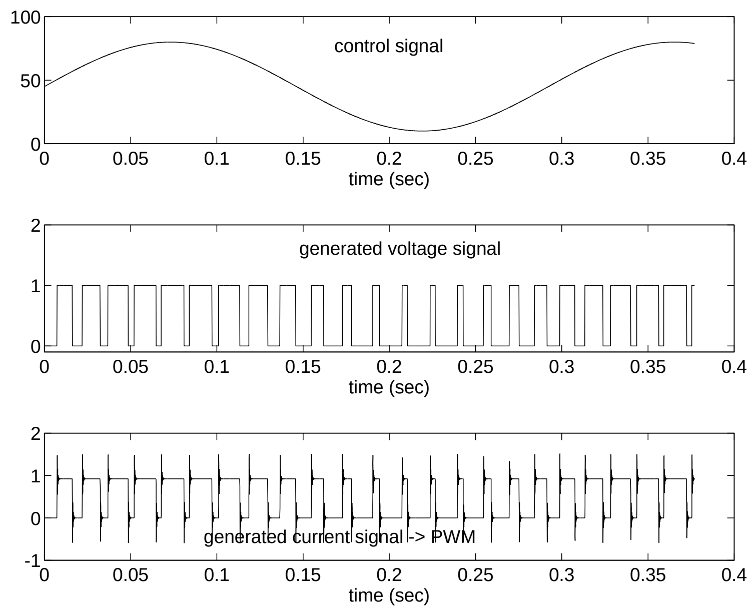

Figure 1: *Generated signals for the PWM control. Top: signal generated by the control unit. Middle: voltage signal, with duty cycle proportional to control unit output. Bottom: current signal send to the PWM valve.*

Measuring the static characteristics

The front panel of this program is shown in figure 4. This program performs a complete set of static measurements on the CVT, as they are done by VCST. One can analyze the relation between one of the servo pressures and one of the output pressures, for different motor speeds or one can analyze the relation between the motor speed and one of the output pressures, for different servo pressures.

The user can assign a physical variable to the x-axis and the y-axis. Afterwards, the initial value, the increment and the final values of the x-axis variables and the parameters are set. Then the program takes over and performs the tests automatically. First a check of all the hardware is performed. This is very important since failure of the current signal generators can cause damage to the CVT, since a pressure drop can cause the pushbelt to slip. Then the program accelerates the motor and automatically sends out all the necessary signals to the CVT and to the motor. Once the signals are send to the system, the program waits till the system has reached a static equilibrium (the data we are interested in!). Then, it measures the data, it updates the screen graphs and it sends all measured values (pressures, temperatures and speeds) to a file. The system also monitors continuously the condition of the test setup and acts in an appropriate way in case of failure. An example of an obtained static characteristic is shown in figure 4 (right side). Instead of doing a lot of experiments it is also possible to generate tests which give the maximum of information with a minimal number of ex-

Figure 2: *A schematic outline of the test setup.*

periments.. This is called design-of-experiments (orthogonal arrays). The test setup performs also tests which are is described in files generated by the design-of-experiments software. All the listed experiments will then be performed one after another.

Measuring the dynamic characteristics

The front panel of this program is shown in figure 5. The program can visualize and store all the measured signals. It consists of a function generator for the three PWM valves. This generator is suitable for most dynamic measurements on the CVT (block waves, ramps, polynomial function). If special waveform are necessary they can be downloaded from file. The set point of the motor speed and the oil temperature can be entered manually. A simple temperature control algorithm runs together with the data acquisition to maintain the oil temperature. All the incoming data is visualized on the screen and stored in a file.

Real-time control

Once the static and dynamic characteristics are measured, these data are used to calibrate or to generate mathematical models. If the models are accurately model-based controllers are designed. After testing the controllers on simulation, they are tested on the real test setup. The developed program takes care for all the signal interfacing, monitoring of the test setup, the control algorithm itself and the storage of the data. For speed considerations, the controllers are implemented in C. The program is designed such that more complicated controllers (LQR, LQG, adaptive,...) can easily be

Figure 3: *The test setup as it is build in the laboratory of ESAT/SISTA at the K.U.L..*

implemented. The sample frequency of the controller is typically 61 Hz, but can be changed. The set points (that form the inputs of the controller) can be entered manually at the control panel or can be supplied in an ASCII-file.

A GLIMPSE ON MODELING AND CONTROL RESULTS

This section shows some of the results obtained in modeling and control with the aid of the test setup. For a full description of modeling and control results, we refer to [Vanvuchelen-1993/1].

Modeling the PWM servo valves

to describe the mean servo pressure realized by the PWM servo valves, it was assumed that the following linear relation held:

$$p_{servo,i} = p_{feed} DC_i$$

with p_{feed} being the (high) feed pressure (4.2 bar) and DC_i being the duty cycle send to i-th servo valve. (1 refers to the secondary, 2 to the primary and 3 to the clutch circuitry).
After a measurement sequence it was (see figure 6) that the assumed linear relationship was not correct; furthermore, after applying polynomial fitting to the measurement data, the following type of model was constituted:

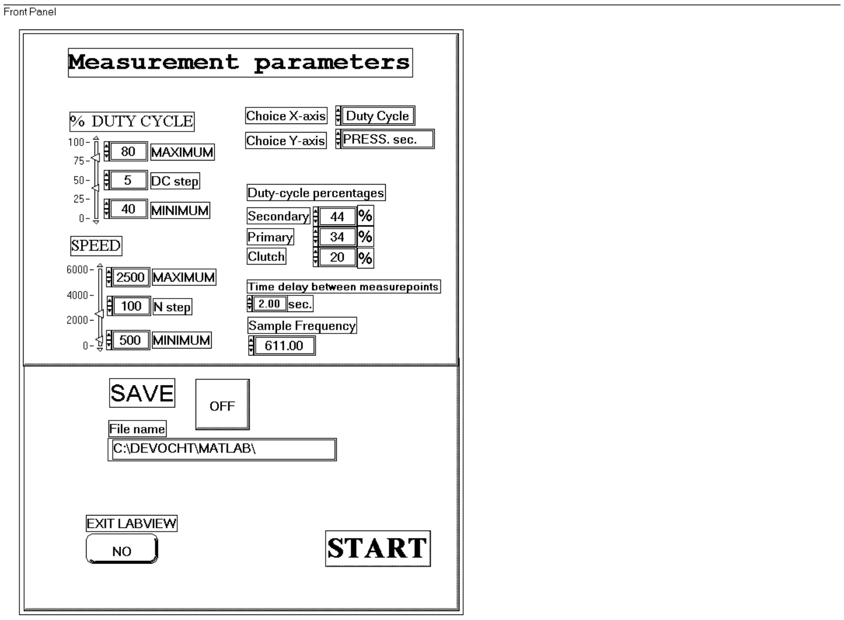

Figure 4: *Front panel of the static data program. In this case, the secondary pressure is measured as a function of the applied duty cycle, for different engine speeds. To guarantee steady state measurements, a time delay of two seconds is used. For safety, the experiments are started with* $DC_s = 44\%, DC_p = 34\%$ *and* $DC_c = 20\%$.

$$p_{servo,i} = p_{feed} f_i(DC_i)$$

with $f_i(.)$ being the polynomials that were obtained by fitting on the experimental data. Figure 6 shows that the polynomial models are much more accurate. Note that the polynomials differ from servo valve to servo valve.

Figure 5: *Front panel of the dynamic data program. Below, one sees the 'knobs' and the function generator to change the inputs (duty cycles). On top, one sees the motor speed setpoint slider and the temperature controller. In the middle, plot windows are used to show the measured data (as a function of time). Other options are the 'save-mode' and 'sample-speed selection'. An emergency stop is implemented also.*

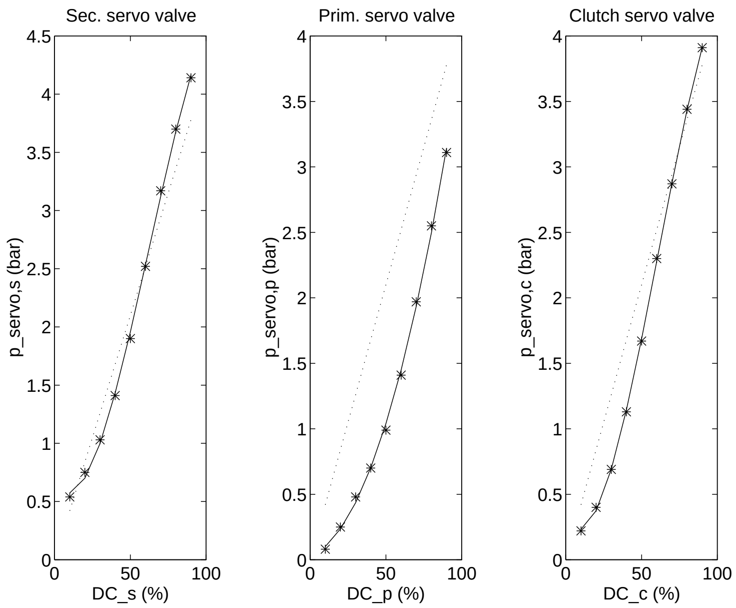

Figure 6: *Comparison between measurements and models of the PWM servo valves. The dashed lines show the assumed linear relations, the full lines show the new polynomial relations.*

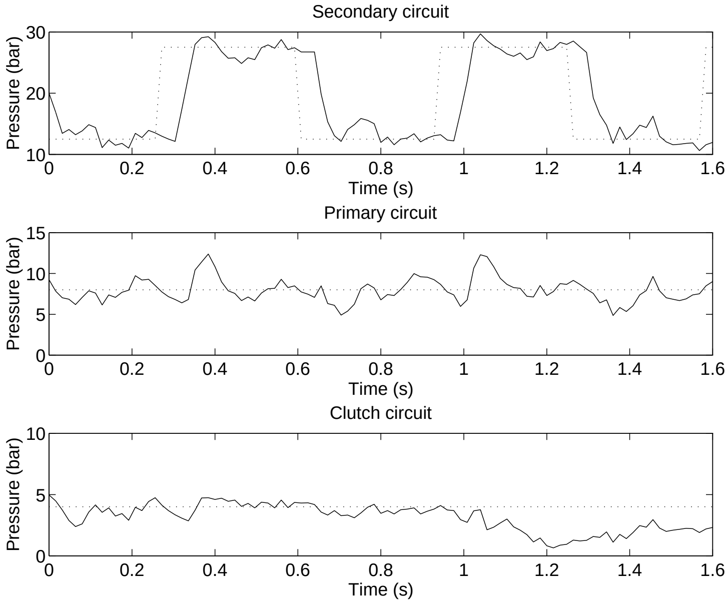

Figure 7: *A control result obtained with three SISO PID-controllers, under the assumption of an almost decoupled system. The controller works acceptable for the secondary and primary circuit, but a better tuned PID on an improved model of the clutch circuitry is required. The dashed lines correspond to the setpoint pressures, the full lines top the realized pressures.*

Three SISO PID controllers for the valve-body

Our valve-body is a MIMO-system (Multiple Inputs Multiple Outputs) with three inputs (DC_i) and three outputs (p_i). In theory, this implies a MIMO-control strategy. However, for simplicity, an almost decoupled system was assumed and three SISO PID-controllers were designed, one for each 'decoupled' circuit. The controllers were tuned on the model of the valve-body, with the aid of multi-objective optimization techniques (see [Vanvuchelen-1993/2] for more information). In figure 7, it shown how the system reacts on a block wave-like setpoint signal for the secondary pressure (tracking), while the primary pressure and the clutch pressure must remain constant (rejection).

REFERENCES

[Vanvuchelen-1993/1] Vanvuchelen P., De Moor B., Reniers D., *A mechatronics approach to electronic control of continuously variable transmissions: towards the limits of performance of combustion engine cars*, submitted for publication, July 1993.

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