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A computer controlled test setup for Continuously Variable Transmissions. [1]

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[1]This report is available by anonymous ftp from *gate.esat.kuleuven.ac.be* in the directory *pub/SISTA/moons/reports/labview.ps.Z*

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Abstract

The technology of a Continuously Variable Transmission (CVT) has been around for many years now. While its reliability, durability, efficiency and controllability have been problems in the past, all but controllability have been greatly improved recently.
In this paper, we present a computer controlled test setup for CVTs. It 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). The system inputs are 3 dutycycles (proportional to hydraulic servo pressures for the CVT), the engine speed and the signal for the oil cooling. The system outputs are 6 pressures, 3 rotation speeds and the oil temperature.
Two Labview programs are developed for open loop experiments; one to measure the static characteristics of the CVT, another to measure the dynamics. The input data can be generated with build-in function generators or via external sequences (e.g. from Matlab). The collected signals can be visualized in Labview (monitoring) or send on the network for model calibration or identification.
The obtained models are used to design controllers of various complexity. To verify the closed loop performance, a program for real time control was written too. For reasons of computation speed and to allow complex control strategies, the controller itself is implemented in C.

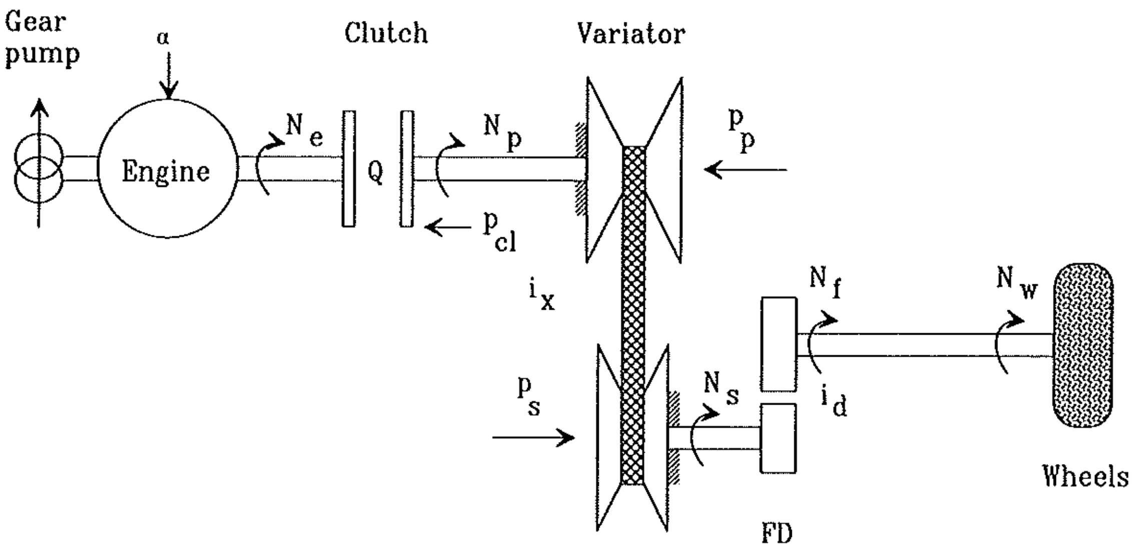

Figure 1: *The powertrain of a car contains a CVT with a wet-plate clutch and a metal pushbelt variator.*

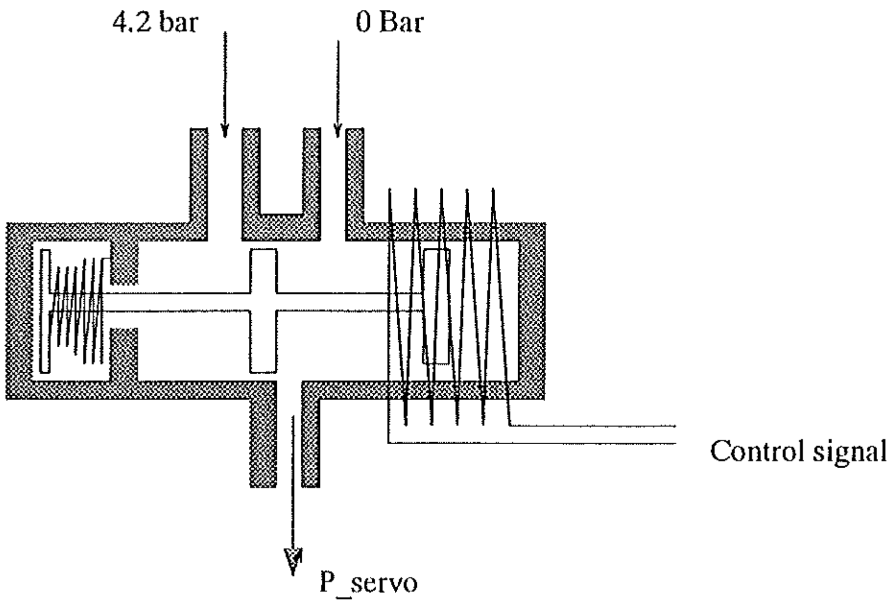

Figure 2: *The output of the PWM servo valve is alternatingly connected to the 4.2 bar line and the 0 bar line. The switching frequency is held constant at 61 Hz, while the duty cycle varies between 0 and 100 (%). By doing this, the mean value of the servo pressure is varied between 0 and 4.2 bar.*

2.2 The engine

Our test setup is powered by an induction motor of 22 kW with a maximum speed of 6000 rpm, with the aid of 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. Communication with the control unit of the test-setup is possible via analogue signals, RS-232 or Profibus.

2.3 The cooling unit for oil temperature control

Since the statical and dynamical 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. Although non-optimality is quite sure (much better solutions can be generated), we remain with it for its simplicity and low-cost.

2.4 Signal conditioning and interfacing equipment

2.4.1 Collecting CVT-data

The signals are measured using a simultaneous sample-and-hold block of National Instruments with a MIO-16 multi-purpose I/O PC-card. In our case, twelve 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

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 with a large bandwidth are used. 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 inverter to the I/O card as an analogue signal ($\pm 10V$).
Finally, all signals (with exception for the water level signal) 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).

2.4.2 Generation of steering signals for the CVT

The outputs of the control unit are generated with a National Instruments AT-A-06 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 analogue signals (with amplitude proportional to duty cycle) to a circuit that generates pulse width modulated block waves at 61 Hz (or 122 Hz). These voltage signals are then send to a current amplifier where the extra pulses are superimposed also. Finally, these signals are send to the PWM valve. An example of the generated signals is given in figure 3
The motor speed set point is an analogue signal that is send to the analogue inputs of the vector controller. The voltage for the hydraulic valve of the cooling system is also an analog signal.

2.5 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. The software is written in Labview. The philosophy of this software is explained further in this text.
A schematical outline of the test set-up is shown on figure 4. Figure 5 shows a photograph of the complete test setup.

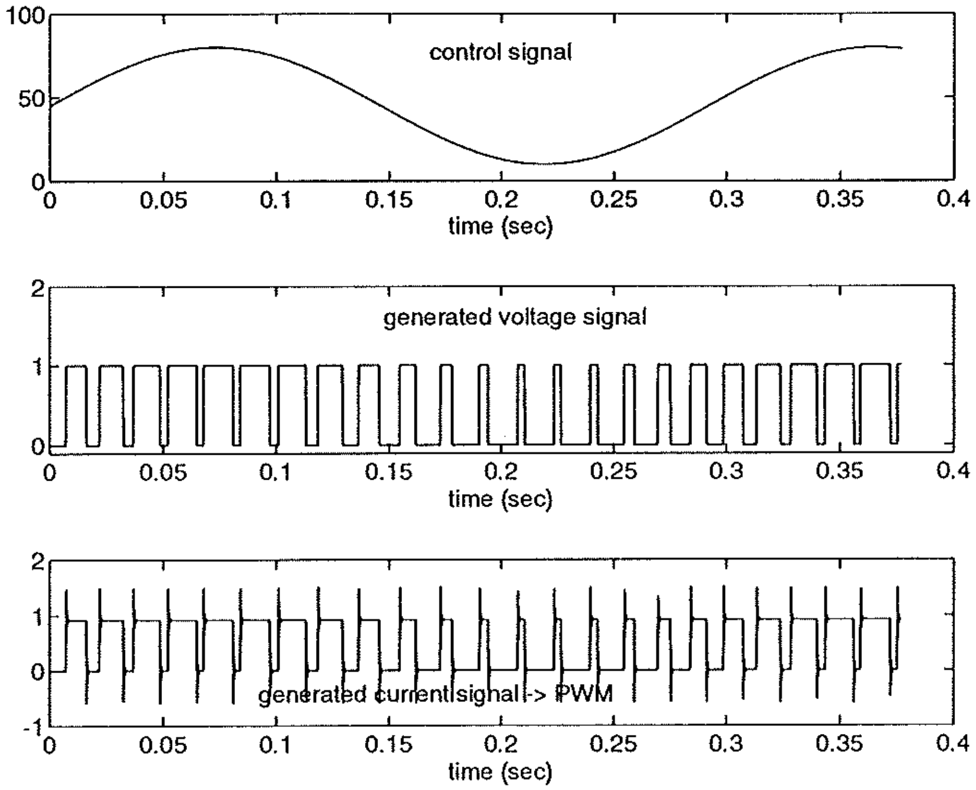

Figure 3: *Generated signals for the PWM control. Top: signal generated by the control unit. Middle: voltage signal, with duty cycle proportional to control unit output. Bottom: current signal send to the PWM valve.*

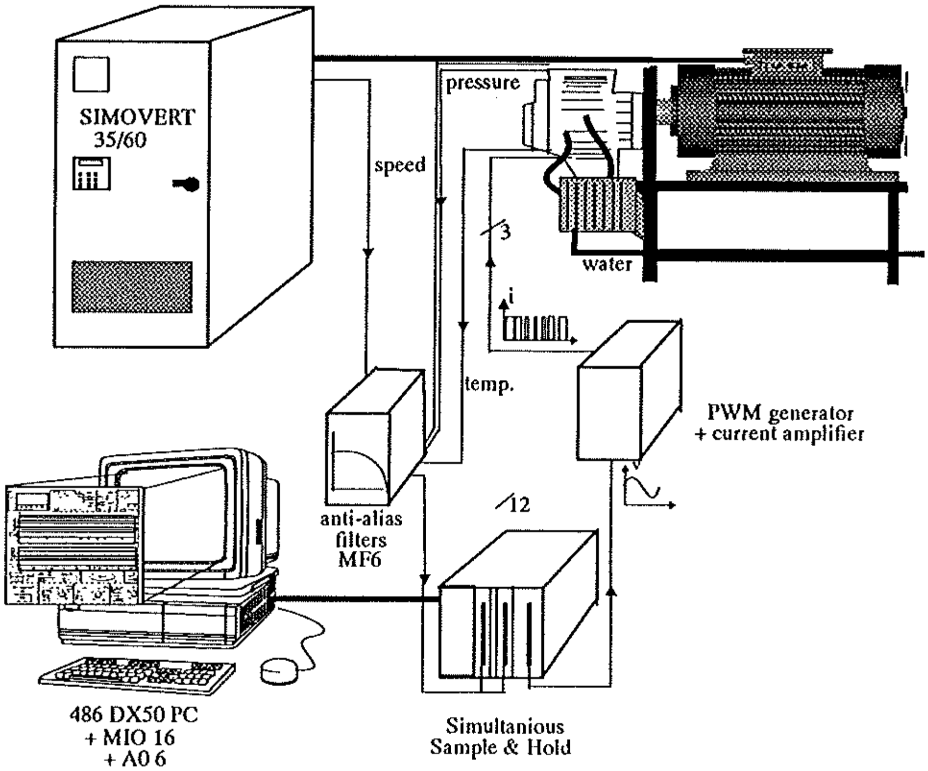

Figure 4: *A schematical outline of the test setup.*

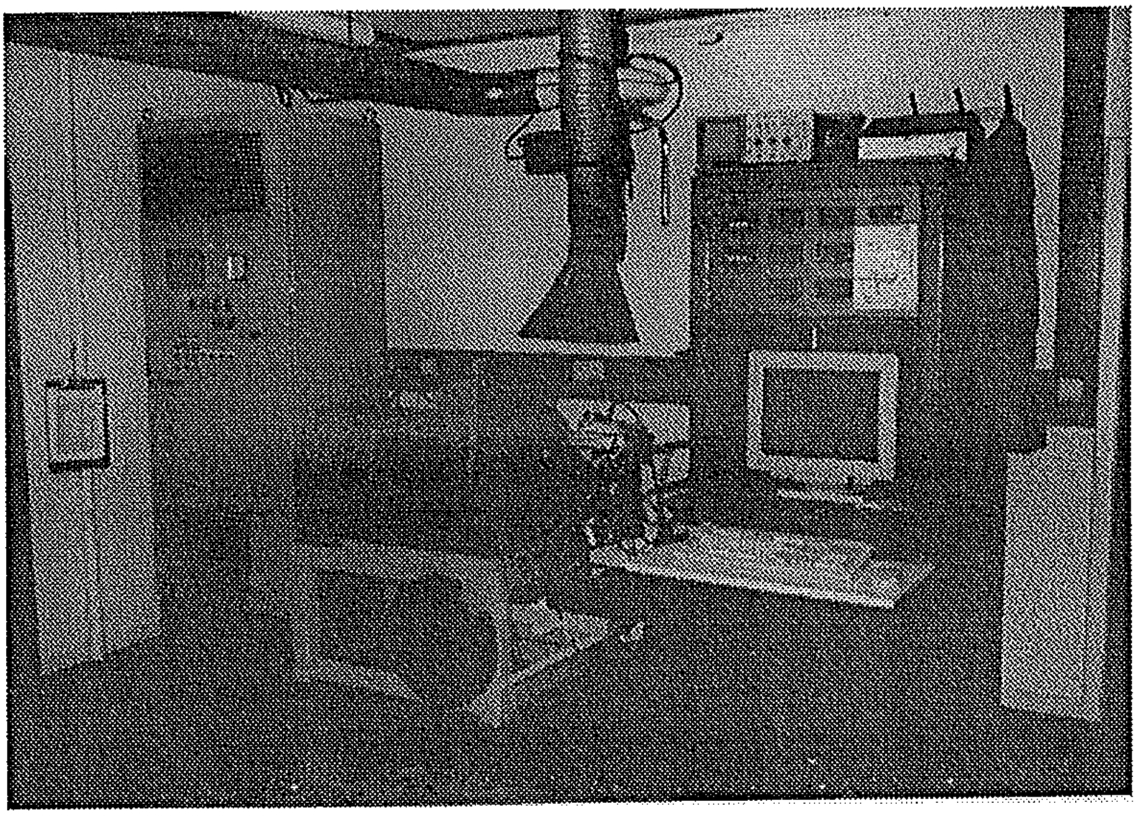

Figure 5: *The test setup as it is build in the laboratory of ESAT/SISTA at the K.U.L..*

3 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.

3.1 Measuring the static characteristics

The front panel of this program is shown in figure 6. 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 define the x-axis and the y-axis. Afterwards, the initial value, the increment and the final value of the x-axis or y-axis variables are set. Then, the program starts 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. An example of an obtained static characteristic is shown in figure 7. Methods based on design-of-experiments (orthogonal arrays) are used to define a set of experiments that allows to generate a maximum of information with a minimal number of experiments. In that case, a list of possible experiments is supplied to the program. All the listed experiments will then be performed one after another.

3.2 Measuring the dynamic characteristics

The front panel of this program is shown in figure 8. The program can visualize and store all the measured signals. The bottom part of the front panel is used to generate (periodic) test signals, that are send to the PWM valves. Three basic signals are available: a block wave, a ramp signal and a polynomial signal. The function generator can create these signals separately or a superposition of the basic signals can be used. Other types of signals can also be generated by putting a desired sequence in a file. This sequence will then be send to the PWM valves. The set point of the motor speed can be set with a slider,while temperature control is possible in the top right part of the panel.

3.3 Real-time control

Once the static and dynamic characteristics are measured, these data are used to calibrate or to generate mathematical models. Since the models are accurately enough, 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. For speed considerations, the controllers are implemented in C. Although PID controllers can easily

Front Panel

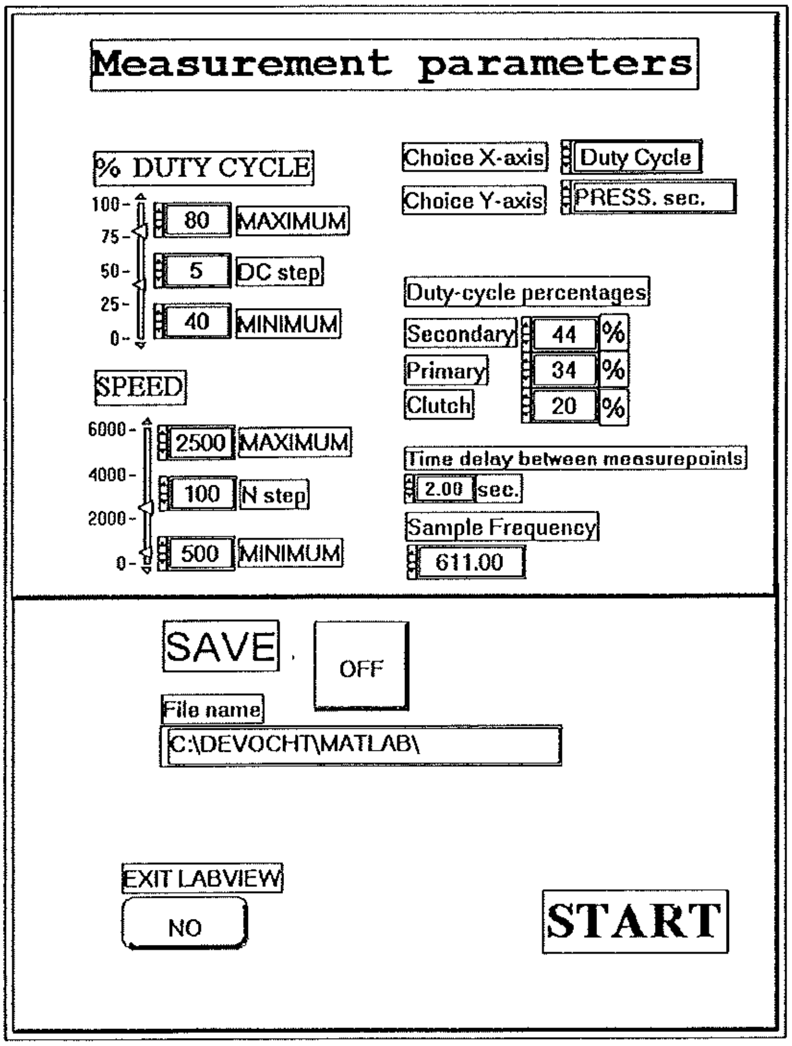

Figure 6: *Frontpanel of the static data program. In this case, the secondary pressure is measured as a function of the applied duty cycle, for different engine speeds. To guarantee steady state measurements, a time delay of two seconds is used. For safety, the experiments are started with* $DC_s = 44\%$,$DC_p = 34\%$ *and* $DC_c = 20\%$.

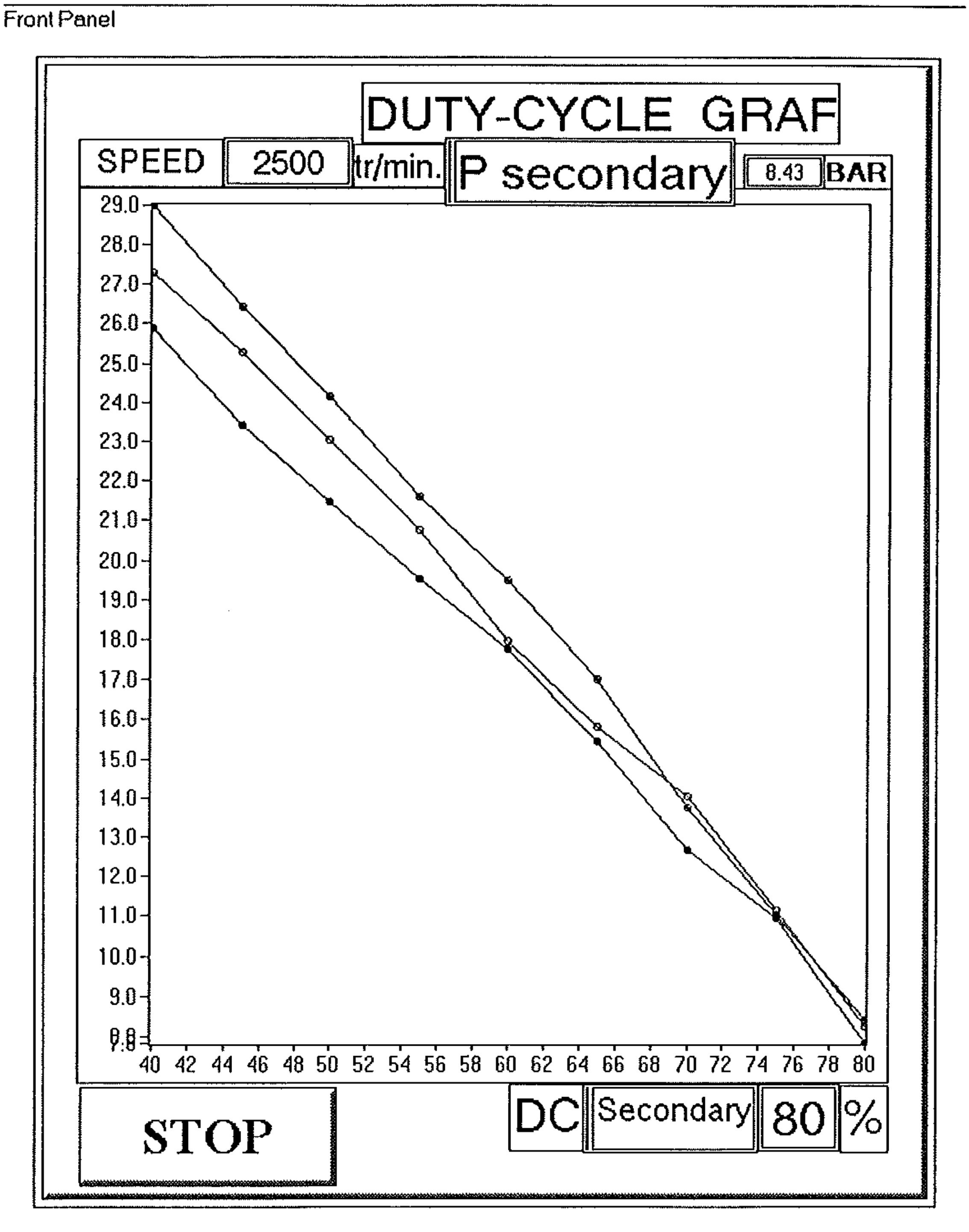

Figure 7: *An example of a measured sequence. Here, the secondary pressure is shown as a function of applied duty cycle, for different engine speeds (see previous figure for full definition of the experiments).*

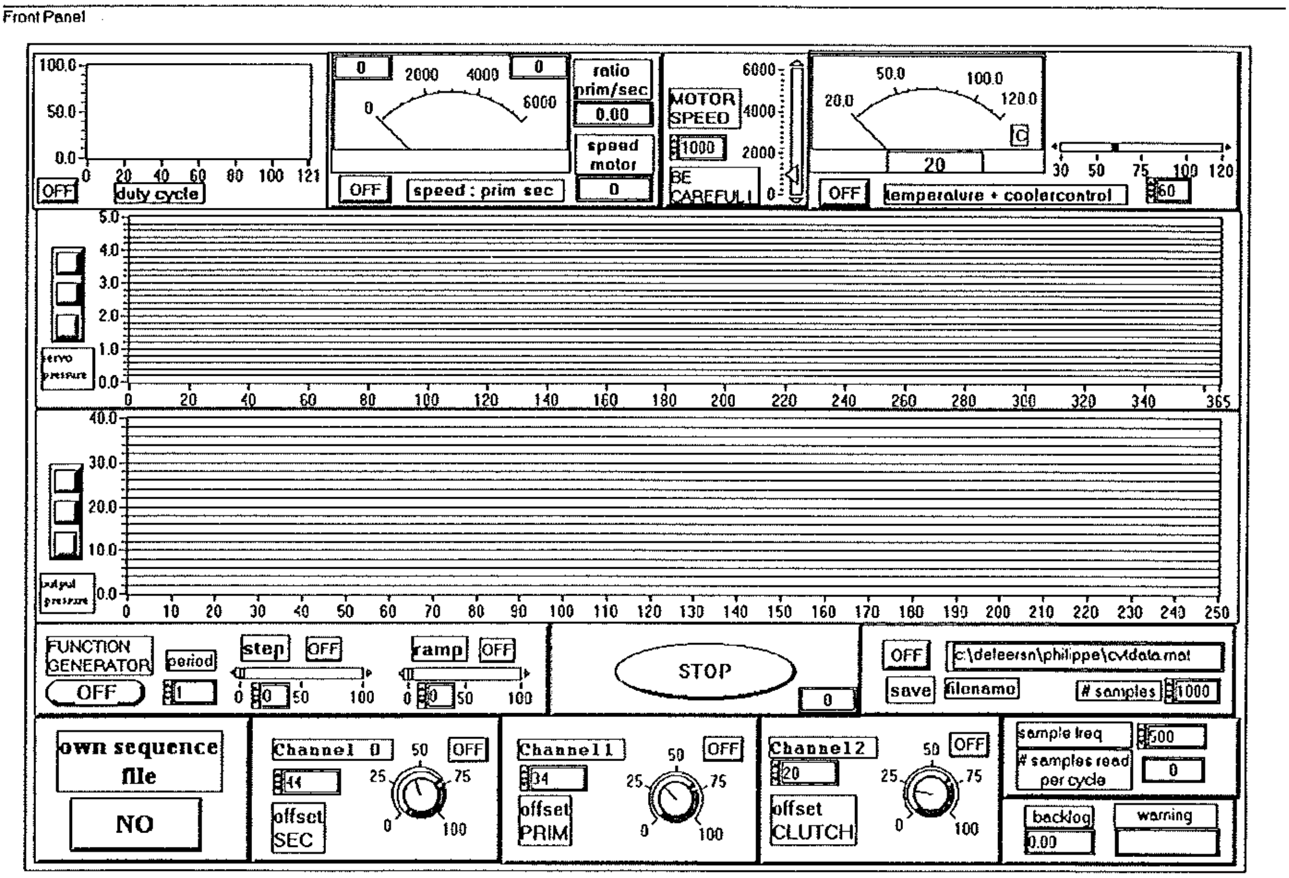

Figure 8: *Frontpanel of the dynamic data program. Below, one sees the 'knobs' and the function generator to change the inputs (dutycycles). On top, one sees the motor speed setpoint slider and the temperature controller. In the middle, plot windows are used to show the measured data (as a function of time). Other options are the 'save-mode' and 'sample-speed selection'. An emergency stop is implemented also.*

be implemented in Labview, complicated adaptive controllers must be implemented in C to restrict the computational load.
The program consists of a loop which is executed at sample rate (61 Hz). Initially, all channels are scanned and the signals are passed to the controller routine (in C). This routine computes the controller outputs and sends them back to the main program. Next, these data is send to the interface cards. To store states or auxiliary variables, extra memory is provided for the controller. 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.

4 A glimpse on modelling and control

This section shows some of the results obtained in modeling and control. Since a complete overview of our modeling and control activities is beyond the scope of this paper, we only treat some selected topics for which the test setup was extremely useful. For a full description of our modeling and control results, we refer to [1].

4.1 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 servovalve [1]. The obtained measurement data are listed in table 1:
From figure 9, it is clear that the assumed linear relationship is not correct; furthermore, after applying polynomial fitting to the measurement data, the following type of model was constituted:

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

with $f_i(.)$ being the polynomials that were obtained by fitting on the experimental data. Figure 9 shows that the polynomial models are much more accurate. Note that the polynomials differ from servo valve to servo valve.

4.2 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

[1]The subscript i refers to the secondary, primary or clutch circuitry.

DC_i	$p_{servo,s}$	p_{servo_p}	$p_{servo,c}$
10	0.54	0.08	0.22
20	0.75	0.25	0.39
30	1.03	0.48	0.69
40	1.41	0.70	1.13
50	1.90	0.99	1.67
60	2.52	1.41	2.30
70	3.17	1.97	2.87
80	3.70	2.55	3.44
90	4.13	3.11	3.91

Table 1: *Static experiments to model the PWM servo valves: the table gives the measured servo pressure as a function of the applied duty cycle, for the secondary, primary and clutch circuit (pressures are in bar, duty cycles in %).*

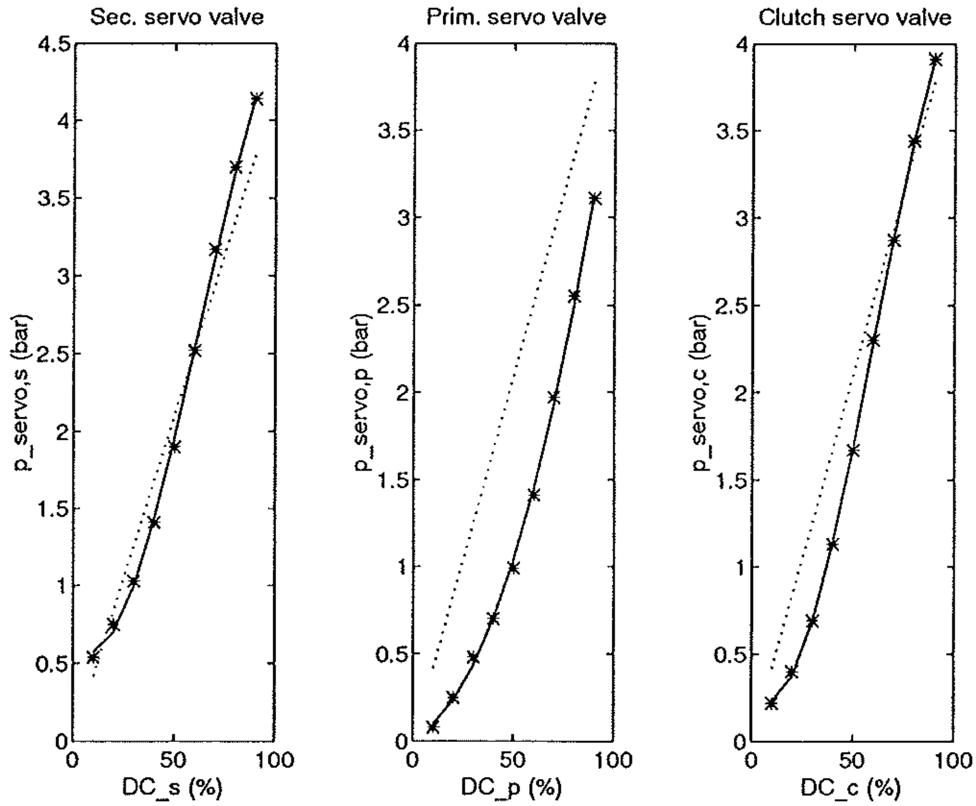

Figure 9: *Comparison between measurements and models of the PWM servo valves. The dashed lines show the assumed linear relations, the full lines show the new polynomial relations.*

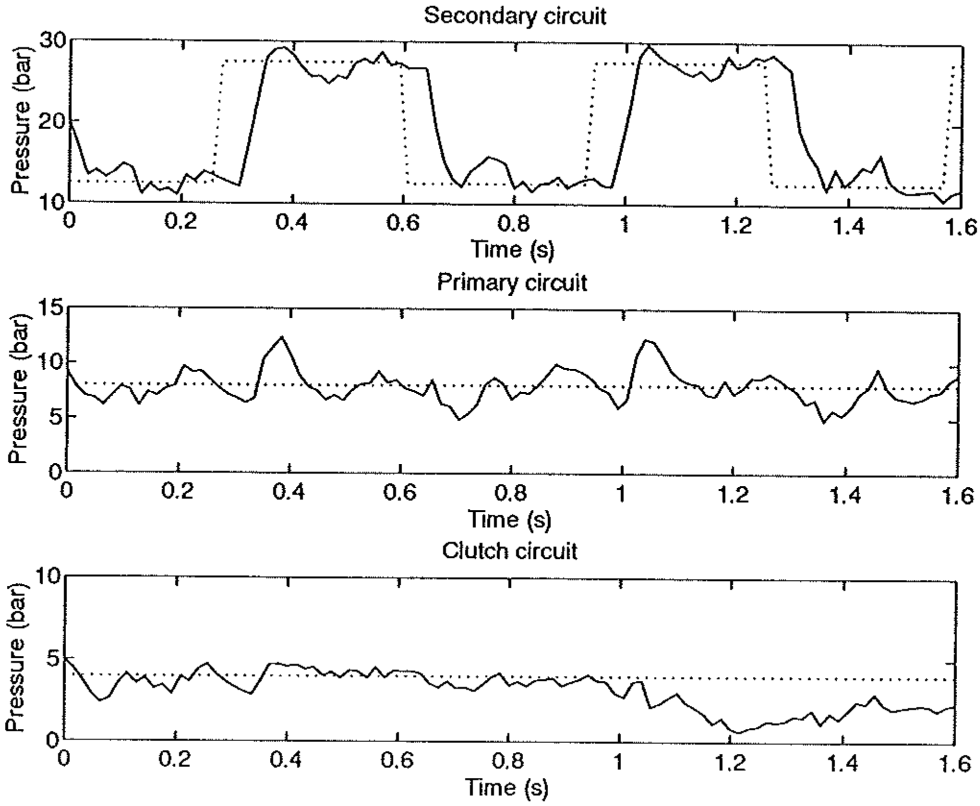

Figure 10: *A control result obtained with three SISO PID-controllers, under the assumption of an almost decoupled system. The controller works acceptable for the secondary and primary circuit, but a better tuned PID on an improved model of the clutch circuitry is required. The dashed lines correspond to the setpoint pressures, the full lines top the realized pressures.*

of the valve-body, with the aid of multi-objective optimization techniques (see [2] for more information). In figure 10, 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

[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.

[2] Vanvuchelen P., De Moor B., *A Multi-Objective Optimization Approach to Parameter Setting in System and Control Design*, Extended abstracts of the IFIP Conference on System Modelling and Optimization, Compiegne, France, 1993.