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MODELING OF AN ELECTRONICALLY CONTROLLED CONTINUOUSLY VARIABLE TRANSMISSION

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ABSTRACT

Accurate and user friendly models of an Electronically Controlled Continuously Variable Transmission (E-CVT) are needed for simulation and control purposes. This type of transmission is based on Van Doorne's *variomatic principle*. This transmission has a lot of benefits compared to the classical automates used in the U.S. and all over the world. To implement a digital controller for the CVT, a new actuator structure (called *valve body*) is needed. In order to reduce the development costs and time, a model based design strategy is required. The bond graph technique seemed the best choice for modeling such a complex system (multiple inputs, outputs and states, statical and dynamical non-linearities,...). The resulting non-linear dynamic models were implemented in Matrix$_X$. This package was choosen because it provides an integrated use of the simulation and analysis process (optimisation, controller design,...). Based on simulations, a lot of practical design information has been generated, i.e. step responses, frequency characteristics, noise suppression curves and optimal values of physical design parameters. When a physical prototype got ready in April 1991, measurements have shown that the accuracy of our models was within a range of 10 percent.

PROBLEM DESCRIPTION

The Van Doorne CVT is shown in figure 1.

One of the key ideas in the design of an electronically controlled CVT [Minten and Vanvuchelen 1991] is to introduce a *software feedback-loop* (Fig. 2) to control the system, in order to increase the flexibility of the transmission vendor towards her clients.

The critical component in this scheme is the *servo system*. This servo system contains a controller, a valve body and and some internal feedback-loops. The coupling between the controller and the valve body is done by *Pulse Width Modulated servo valves (PWM valves)*.

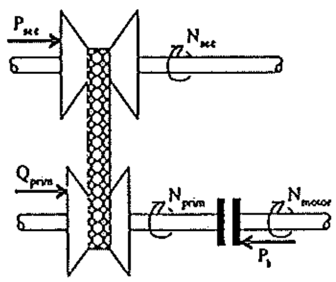

Figure 1: The classical variomatic principle

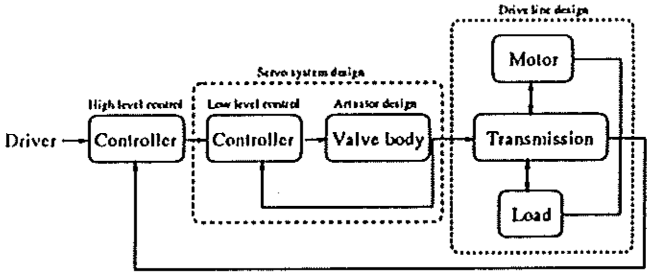

Figure 2: Control scheme for an E-CVT

They transform electrical servo signals into hydraulic ones. The PWM frequency is assumed to be high, compared to the bandwidth of the system connected to it. Hence, the dynamics of the PWM valves can be neglected. In the valve body the *hydraulic valves* transform these hydraulic servo signals into hydraulic actuator signals, in such a way that certain static and dynamic specifications are satisfied.

The circuit in Figure 3 serves as an example. The valve controls the flow towards a cylinder.

An open-loop system however in itself can not always meet the desired specifications. To ensure that some critical actuator circuits have the prescribed behaviour, an *internal feedback-loop* (*low level control*) must be

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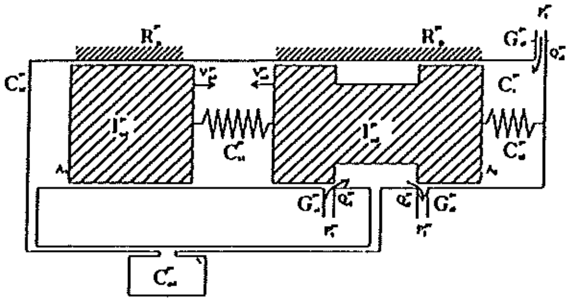

Figure 3: A valve for flow control

added. An example of such a critical circuit is the pinch pressure circuit. This circuit is used to prevent the transmission from slipping. If the pressure is high enough, the belt doesn't slip. But the efficiency of the total system decreases. On the other hand when the pressure is to low, the belt slips and the transmission is destroyed.

Notice that the valve body contains different coupled hydraulic circuits. Initially, these circuits will be treated as nearly decoupled in order to maintain classical control strategies such as PID control. Afterwards more modern control strategies will be used. By means of state feedback control laws, the performance and robustness can possibly be improved.

In this paper, a model-based approach for designing such servo systems is developed. In Section 2, it is explained how such systems can be modeled, while Section 3 covers the implementation aspects of such models. Finally, Section 4 contains some results on the actuator design and on low level control.

SYSTEM MODELING

In the literature, several techniques are described to model physical dynamic systems. Engineers are most familiar with block diagrams or differential equations. Major drawbacks of these models are the lack of structure during the model generation phase, the absence of the structure of the physical system in the generated model [Karnopp 1989] and the causality problems that arise when subsystems must be coupled. When dealing with small dynamic systems, these negative points introduce only few problems, but for large dynamical systems, these classical methods are almost never error-free.

The Modeling Method

Most of the problems mentioned above are caused by the fact that engineers want a computable model. However, this is not the goal of the modeling phase which is to obtain a true representation of the physical dynamic system. When constructing a bond graph model, the modeler can split up those two different aspects. Creating a bond graph gives form to the modeling phase (dealing 'equations'); analysis of the computational causality of the bond graph will result in a computable form of the model (dealing 'assignment statements'). There is a tendency to consider this last issue as a pure mathematical problem that must be solved by the computer. But in the case of the servo system, simulation is not the only objective of modeling. The models will be used in two different ways. In the *actuator design phase*, the influence of springs, friction coefficients and masses is determined, in order to optimize the system itself. Here causal problems like algebraic loops can be solved by implicit integration algorithms. Next, in *low level control*, controllers are designed in order to obtain specifications such as tracking and robustness. When dealing with modern model based control strategies, a state space representation is needed. In this phase, causal problems must be solved in a different manner as in the actuator design phase. It is surprising that while retaining the structure of the physical dynamic system, the bond graph can be used for both the actuator design phase and the low level control phase.

The Bond Graph Type

The system to be analyzed consists of several mechanical and hydraulical subparts. While constructing a bond graph, the main concern will be the calculation of the *the average volume flow rates* through orifices and *pressures* in the hydraulic subsystem, and the macro fluid dynamic interaction with the solid mechanical elements (valves, cylinders,...). Under these approximations an exact bond graph representation is not nesessary, even inconvenient [Karnopp and Rosenberg 1975]. We will use here the familiar lumped parameter model proposed in [Dransfield 1981], because the hydraulic subsystem is in fact a servo mechanism for which the volume flow rates are rather low and the high order dynamics of the hydraulic inertias can be neglected.

MODEL IMPLEMENTATION

As stated earlier, the main objective is to automate the design process of the servo system. Therefore different model types have to be made. In the design phase, the models must contain every physical component in order to optimize the component values or even the structure. However, the use of these complex models in low level and high level control is not obvious. This because they result in long simulation runs. Since the reduction of these nonlinear models is not always structured, a lot of research must be done in this area. As a rule of thumb, the statement that only the macro influence between the subparts has to be modeled, can be used.

The Choice Of The Software Package

Nowadays there exists no excellent *integrated software* dealing with modeling, simulation and analysis together [Valk 1992]. Bond graph pre-processor types like CAMP have the disadvantage that the syntaxis of ACSL must be known in order to edit the processed bond graph for non linearities etc. Althoug this editing possibility is flexible, it is not integrated. Bond graph simulators like CAMAS don't have these drawbacks but the analysis of the constructed models is not (yet) supported. Only programs like Matlab and Matrix$_X$ provide an integrated approach of the simulation and analysis part of the project. Implementation of classical control laws (PID) or more modern methods (state feedback, pole placement,...) can be used in these packages. But the input file must consist of (causal) block diagrams -or alike- structures. The conversion of a bond graph to a block diagram is thus nessessary in order to handle the modeling, simulation and analysis part in a structured and powerful manner. Because the graphical input capabilities and the hierarchical library structure of Matrix$_X$ were superior to Matlab, the former is used as the software tool for simulation and analysis.

The Library Construction In Matrix$_X$

Matrix$_X$ has nice capabilities to construct structured or nested block diagrams. The use of those so called *superblock* structures reflects very well the construction of the *causal word bond graph* [van Dixhoorn 1979]. Figure 4 represents a diagram of the major substructures.

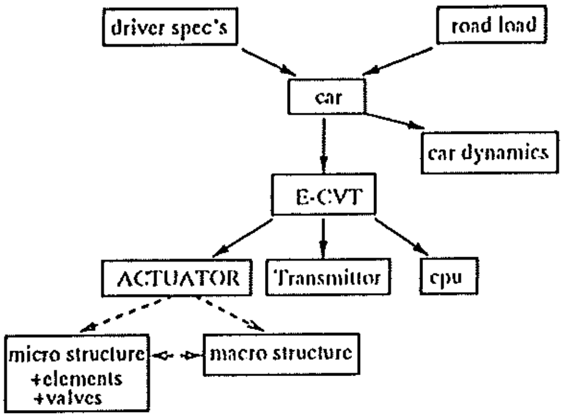

Figure 4: The hierarchy between the different dynamic models.

Different physical phenomena take place in the actuator. At the first level, models of these elementary physical phenomena are generated. One level higher, these models are used in the construction of the models of the different valves. Those two levels deal with the actuator design phase, taking into account the micro structure of the valve body. Structural design and physical parameter optimization are the main objectives here. The third level will include the related transmittor dynamics and the properties of the processor unit. These models can be used in internal loop design for the servo system. Specifications on the servo system dynamics are the main subjects here.
As a next step towards general system design, a fourth level is planned. At this level, models of the road load, the car dynamics and the motor will be build. These models will then be used for *high level control* of the E-CVT. Specifications on the drivers comfort, on noise generation and on fuel consumption will be the main control problems. In order to achieve the nessessary models of the actuator, only the macro structure is considered here.

SOME RESULTS IN SERVO SYSTEM DESIGN

For reasons of confidentiality, all specifications and simulation results in this paper are normalized.

Actuator Design Phase

This example treats the valve shown in Figure 3. Although the servo pressure p_{servo} acts directly on the mass m_2, and not on the mass m_1, this valve translates p_{servo} into a horizontal displacement x_1 of the mass m_1. Because the oil temperature T strongly influences the behaviour of the valves via the oil viscosity ν and the oil density ρ, it is added as an extra input. The bond graph model and the Matrix$_X$ calculation scheme are shown in the figures 5 and 6. In the bond graph, the symbol G (conductance) is sometimes used instead of a R (resistance), showing more explicitely the causal assignments to the resistive field.

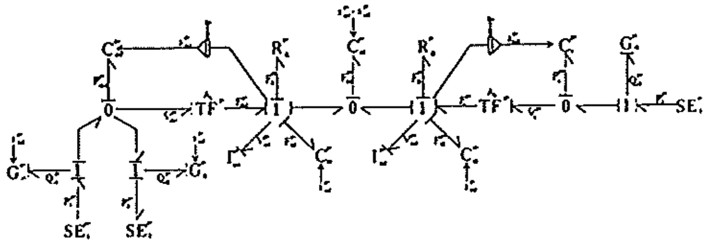

Figure 5: Bond graph model

The design specifications for this valve are the following:

- *Linearity specification*: The relation $x_1(p_{servo})$ must be linear. When p_{servo} varies between 0 and 10 (bar), x_1 must go from −10 to 10 (mm).
- *Relative displacement specification*: Compared to x_1, x_2 must be small (< 10%), to limit the flows out of the constant pressure reservoir.
- *Tracking and settling time specifications*: For steps and ramps as input.
- *Robustness specification*: Robustness against variations in the oil temperature.

Some design results are shown in figure 7, 8 and 9. Figure 7 gives a simulation-based proof of the empirical assumption that the given structure satisfies the relative displacement specification. The servo pressure p_{servo} and the responses are shown.

In figure 8, the influence of the mass m_2 is shown. Further, figure 9 shows the influence of the mechanical friction R, which is proportional to the roughness of the drilling-operation.

Low Level Control Phase

This example considers the design of an internal feedback-loop for the pitch pressure. An ideal physical model of the valve to be controlled is given in figure 10. The servo pressure p_{servo} is transformed into the pitch pressure p_{pitch}. The open loop behaviour of the ideal

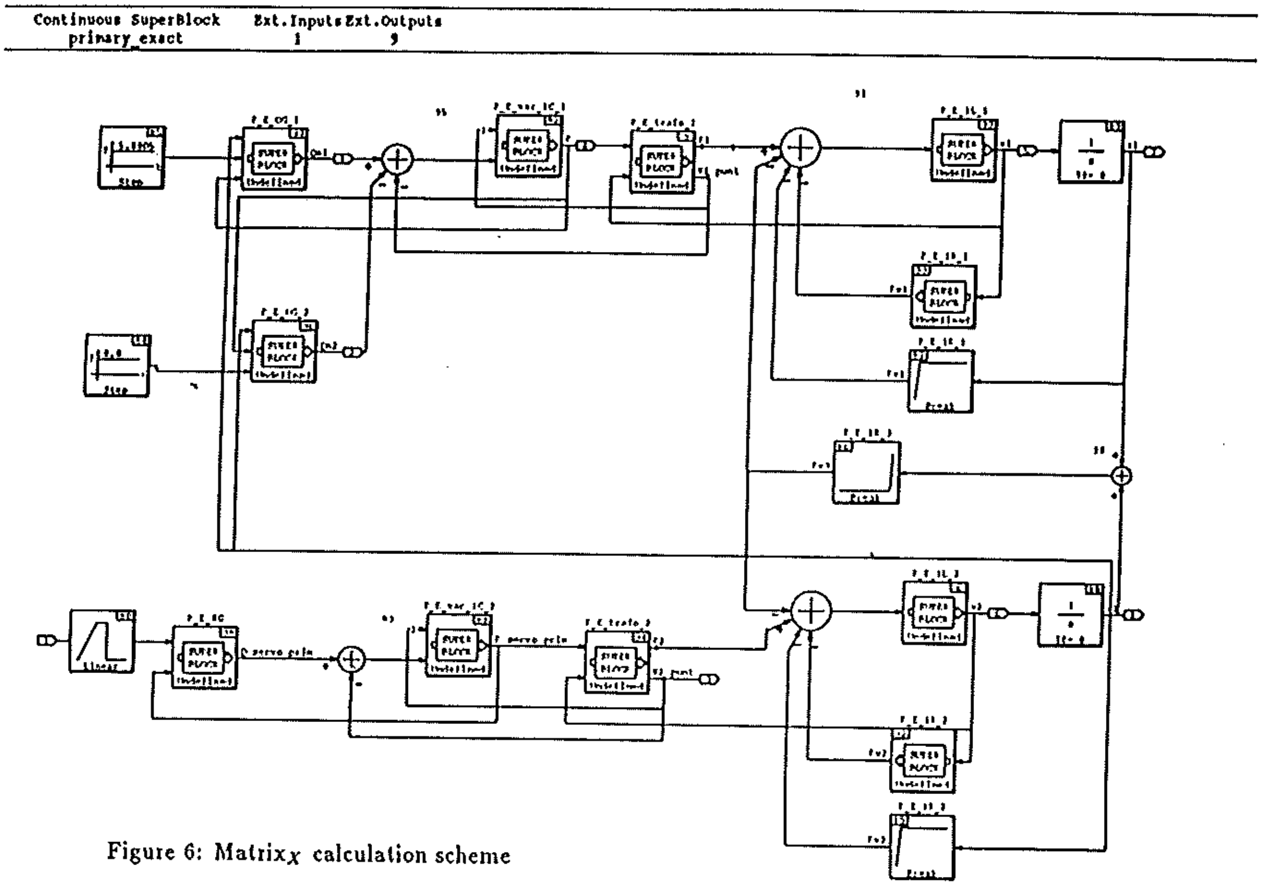

Figure 6: Matrix$_X$ calculation scheme

valve (i.e. most optimal parameter values used) for a step of height 4 (bar) is shown in figure 11. One of the design specifications is a settling time of $1ms$, independent of the oil temperature. This simulation shows clearly that the design specifications are infeasible when only open-loop design is considered. Therefore, in order to increase the actuator performance, an internal loop must be added to the system (fig. 12). In the future not only *PID* controllers, but also more robust controllers (μ control) will be investigated.

CONCLUSIONS AND FUTURE RESEARCH

In this paper an integrated approach of modeling, simulation and analysis of a complex industrial problem is proposed. Although empirical rules can be derived intuitively by experienced designers, our approach is very useful for different reasons:

- The bond graph method connects different physical domains. This forces the designer to think about the system in a generalized way.
- Simulations allow the designer to quantify the influence of parameters.
- Simulations allow the designer to visualize the system behaviour using graphical output.
- Simulations allow the designer to get more insight in the system, because internal signals, that are not measurable in real life, can also be visualized.

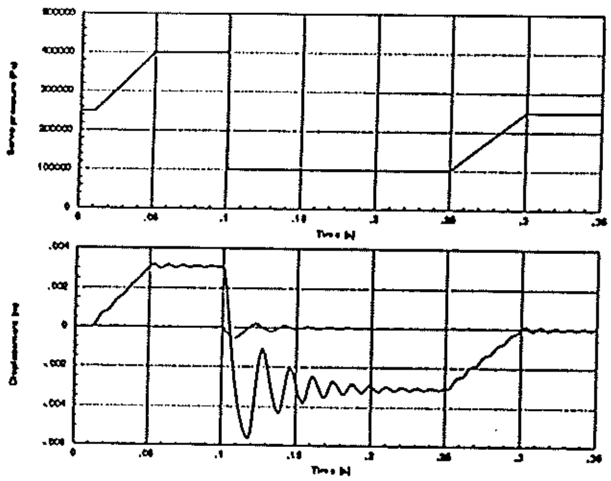

Figure 7: Displacements of m_1 and m_2 (lower part) as a function of the servo pressure (upper part). The full line represents the displacement of the mass m_1, while the dotted line gives the displacement of the mass m_2. One can easily see that the relative displacement of the mass m_2 is under all circumstances small enough.

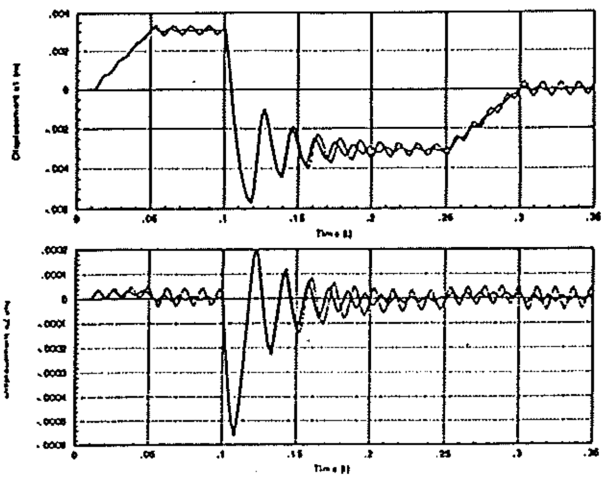

Figure 8: Influence of the mass m_2 on the displacement x_1 and x_2. The full line represents the behaviour of the default value of the mass m_2, while the dotted line corresponds to a higher value. For an increased value m_2, one can easily see that the system is less damped.

- Simulations are less costly and much faster to do than real life experiments. This allows the designer to consider more alternatives when seeking for a suitable design. In most cases, this means that a better design can be found in a shorter time, with less money.
- Simulation and analysis can be done by menu driven, user written software. As a consequence, the whole servo system design phase can be highly automated.

In the near future, this research will be extended. To study the behaviour of the complete car, models of the motor, the transmission and the load are needed. These models can then be used to evaluate the complete car and/or to design the general car control system (*high level control*).

ACKNOWLEDGMENT

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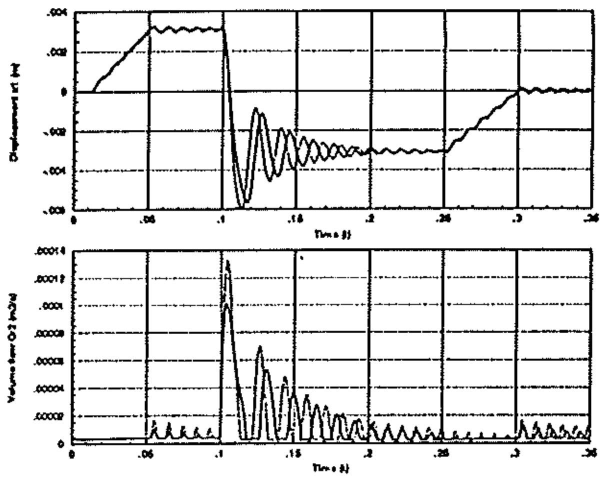

Figure 9: Influence of the mechanical friction. The full line represents the behaviour with the default value of the friction R, while the dotted line corresponds to a smaller value. For a decreased value R, one can easily see that the system is less damped.

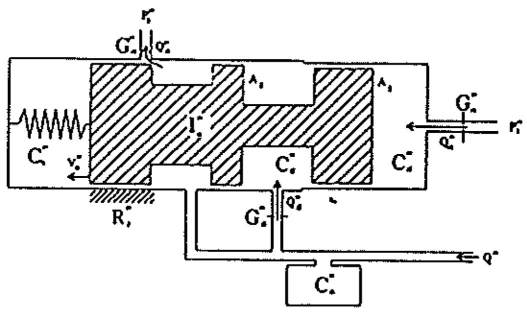

Figure 10: An ideal physical model of the pitch pressure valve

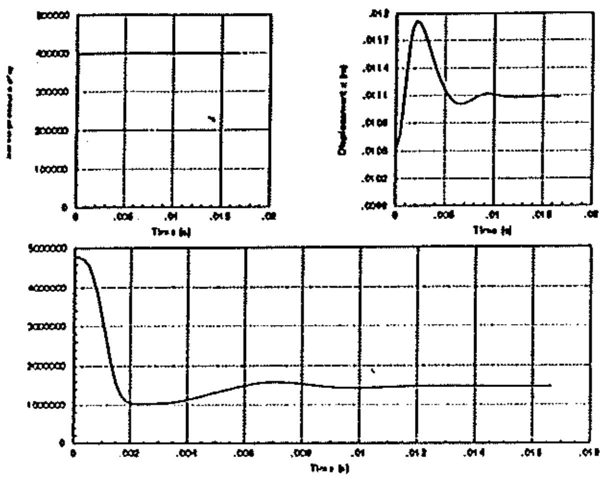

Figure 11: Open loop behaviour of the valve

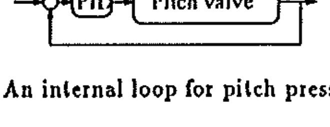

Figure 12: An internal loop for pitch pressure control

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