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Multidomain Systems: Electronic, Hydraulic, and Mechanical Subsystems of an Universal Testing Machine Modeled with Modelica

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Abstract

The Simulation of hydraulic or electronic systems has been state of the art for a long time. For both of these domains there exist highly specialized simulation programs which can be regarded as a kind of industrial standards. Often problems arise if different domains of technology occur within one system and very detailed models are needed.

As an example a universal testing machine is presented which consists of hydraulic, mechanical, and electronic component systems. Each component is modeled fully detailed using the **Modelica** language [1]. Without coupling of simulators the whole simulation model can be investigated by **one** tool.

1 Introduction

The engineer of today is used to powerful simulation tools. Within the last fourty years these tools mutated from simple solvers of differential equations to computer-aided design software for technical systems. Tools like HSPICE in electronics, ADAMS in mechanics, or HOPSAN in Hydraulics are highly specified to meet the needs of the discipline. These tools “know“ the domain-intern pecularities. Often the models and the simulation algorithms are closely related. Therefore, these tools are very advatageous in simulation, modelling, and postprocessing.

Often problems arise if technical systems cover more than one established discipline, e.g. in microsystems engineering. The two fundamental ways out are coupling of simulators, and compact modeling for one simulator.

From the very beginning the Modelica language is designed for covering several technical disciplines [2], [3], [4]. Complex systems can be modeled with **one** language to get **one** model. The further processing within the Dymola simulator results in **one** methematical model, typically a differential algebraic equation, which is solved by **one** simulation core. The challenge of the Modelica approach is to show that its efficiency is not much less than the efficiency of domain specific tools. To offer evidence of this is surely a long process. In this paper the multidomain example of a universal testing machine is presented. It demonstrates that the unified multidiscipline simulation tool Modelica/Dymola meets the challenge quite well.

At first the physical device is presented with emphasizing the hydraulic and electronic parts. The Modelica model is shortly described, and simulation results are discussed. It is shown that numerical problems could be solved, and the performance can be accepted.

2 The Universal Testing Machine

Fig. 1 shows the universal testing machine. It is a simple mechanical construction of a one-sided working Plunger cylinder and a hydraulic unit on the left side in the picture. The hydraulic unit consists of a small AC motor, a variable displacement pump, and a pressure limiting valve.

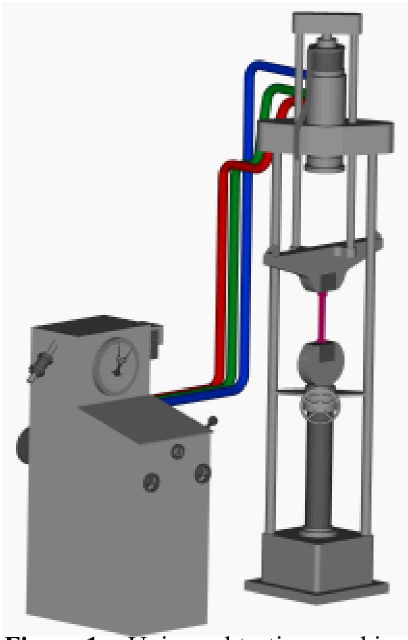

Figure 1: Universal testing machine

This kind of machines is used for tensile tests of a rod to detemine e.g. the tensile strength, which is a material property. The resulting **quasi-static** stress-strain diagram describes how the material reacts under a continuously increasing load. Often the load is necessary to be regarded not as static but as periodic. In these cases the testing method has to be modified to get pulsating forces. A simple modification is like this: Within the hydraulic circuit an electro-hydraulic proportional valve of high quality is inluded as a by-pass to the cylinder. This valve is controlled using a sine-wave generator as reference input and a PI-controller. The machine is described in more detail in [5].

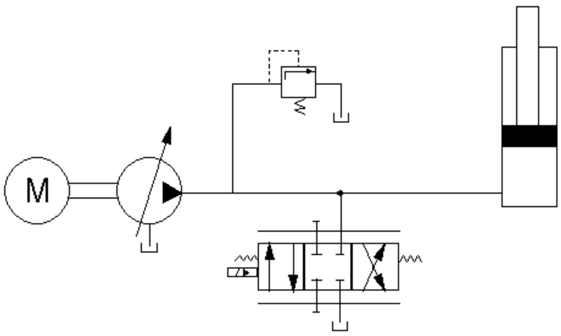

Figure 2: Hydraulic circuit of the testing machine

The task of the simulation is the investigation of the modifications before they are aplied. E.g. the characteristic parameters of the valve and the electronic controller have to be determined.

3 The Hydraulic and Mechanical Parts

After preliminary work using the analogue computer in the fifties the simulation of hydraulic systems became important in the eighties. Graphical user interfaces were added in the nineties [6]. Using Modelica and its libraries it is easy to model hydraulic or mechanical systems [7]. The user needs not absolutely know the details of component modeling. If nevertheless details are essential the source code of the models is available.

Using HyLib models the hydraulic circuit according to **fig. 2** could be modeled. Since the pump is driven via a V belt transmission parts of the standard Modelica mechanics library are used to built the model according to **fig. 3**. A further mechanical component is the model of the specimen which is a linear spring.

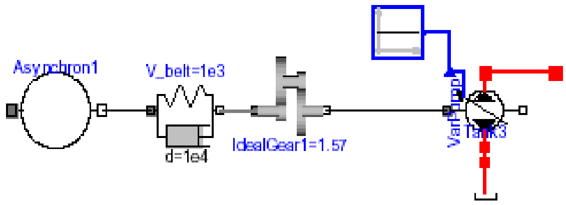

Figure 3: Model of oil source

To enable dynamic testing an electro-hydraulic valve is used as a by-pass to the cylinder. In more detail the hydraulic and mechanical parts are described in [8], [5].

4 The Electronic Part

Since 1975 SPICE [9] is available for the simulation of electronic and especially for microelectronic circuits. Later on, powerful circuit simulators with graphical and textual input possibilities were designed on SPICE. For electronic devices very comprehensive models are available which sometimes are based on semiconductor technology parameters.

In the electrical analog Modelica library [10] the most often used electrical components are collected which are easy to understand and of a wide interest. Although the SPICE semiconductor devices are still missing it is possible to model rather complicated electrical circuits.

The electronic part of the testing machine is a PID-controlling device [11], which amplifies (**p**roportional), **i**ntegrates, and **d**ifferentiates the input signal. The circuit scheme can be seen in **fig. 4**.

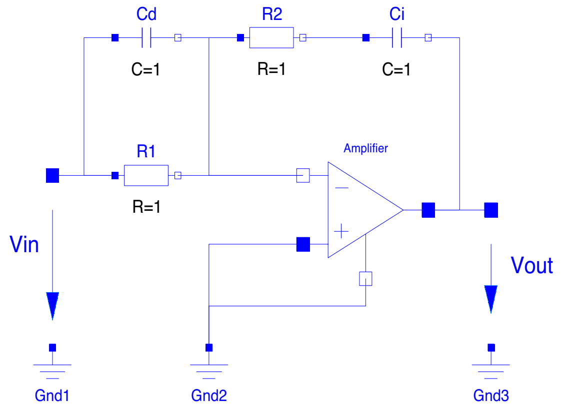

Figure 4: PID circuit

By chosing the resistances and capacitances according to

$$P = \frac{R_2}{R_1} + \frac{C_D}{C_I}, I = \frac{1}{C_I R_1}, D = C_D R_2$$

the controlling parameters P, I, and D can be adjusted.

$$V_{out} = PV_{in} + I\int V_{in} dt + D\frac{dV_{in}}{dt}$$

The operational amplifier was modeled on different abstract levels. On the transistor level the well-known µA741 [12] was used which is modeled using bipolar transistors (14 NPN, 7 PNP) of the Modelica standard library.

The numbers of the values of currents in the electronic part are orders of magnitude smaller than the numbers of values in the hydraulic part. Small capacitances in the transistors cause very short transient responses. Therefore the mathematical model becomes stiff, which is a challenge for the simulation system.

The bipolar transistors are modelled in the most simple way according to the Ebers-Moll-approach [13], [14]. The circuit structure (**fig. 5**) shows the components

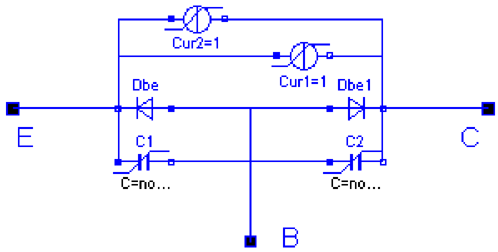

Figure 5: Ebers-Moll transport model

which are nonlinear ones. Since the currents of the nonlinear sources depend on the diode currents the transistors are modelled using a behavioural description instead of a structural one. Both the diodes and the capacitors use exponential growing functions. Because of numerical reasons these functions are linearized, if their results grow extremely.

The characteristic of an NPN transistor is shown in **fig. 6**. The collector current is growing exponentially if the base-emitter-voltage exceeds a certain value. In detail the characteristic depends on 16 parameters which are explained in the Modelica Standard Library.

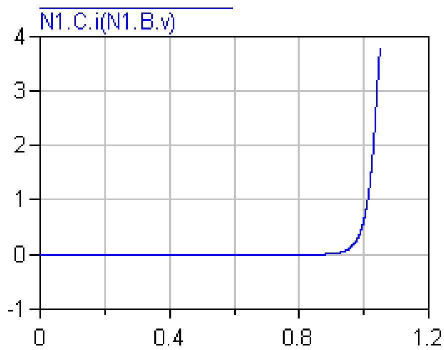

Figure 6: NPN characteristic

5 The Modelica Model

The simulation model of the controlled universal testing machine is shown in **fig. 7**. The mechanical and electronic models are from the Modelica Standard Library [1], the hydraulic models from the HyLib [7].

Unfortunately, the µA741 operates in a very small voltage range. Otherwise it runs into saturation. To avoid saturation effects, both the input signal and the output signal of the controller are transformed using the Gain model of the Modelica standard blocks library. The

Gain model simply multiplies the signal by a constant factor. The input signal is multiplied by 4.0e-7, the output signal by 0.1.

The electronic library uses the pin definition:

```
connector Pin
  SIunits.Voltage v;
  flow SIunits.Current i ;
end Pin;
```

For the block library the port definition is (the OutPort definition is quite similar):

```
connector InPort
  parameter Integer n=1;
  replaceable type SignalType=Real;
  input SignalType signal[n];
end InPort;
```

When electronics is coupled with block library elements these connector definitions hit each other. Since the voltage carries the information which is relevant for the signal processing the voltage is mapped on the signal value. This is simply done using the elements SignalVoltage, which converts an InPort signal value into an electrical voltage, and the VoltageSensor, which does it vice versa.

6 Results

With Dymola version 4.1a [15] the model of the universal testing machine was composed graphically, analyzed, translated into executable code, and simulated.

The simulations started at the quiescent state (all voltages are zero, the hydraulic pressures are equal to the environment pressure) at time zero and finished after 10 seconds in the steady state. Several simulations with parameter variations were necessary. As a result the nominal valve value and parameters of the controller could be chosen. Both the maximum excitation frequency and the maximum force reachable could be calculated. Measurements which were done afterwards at the real machine confirmed this choice of parameters. In the following pictures the behaviour of some variables is shown.

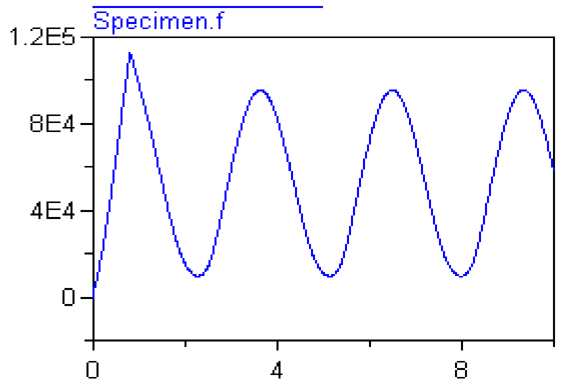

Figure 8: Force acting on the specimen

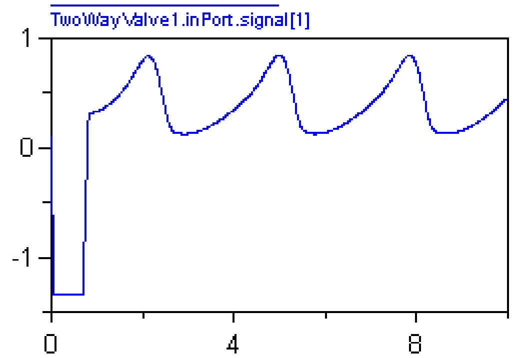

Figure 9: Valve input signal

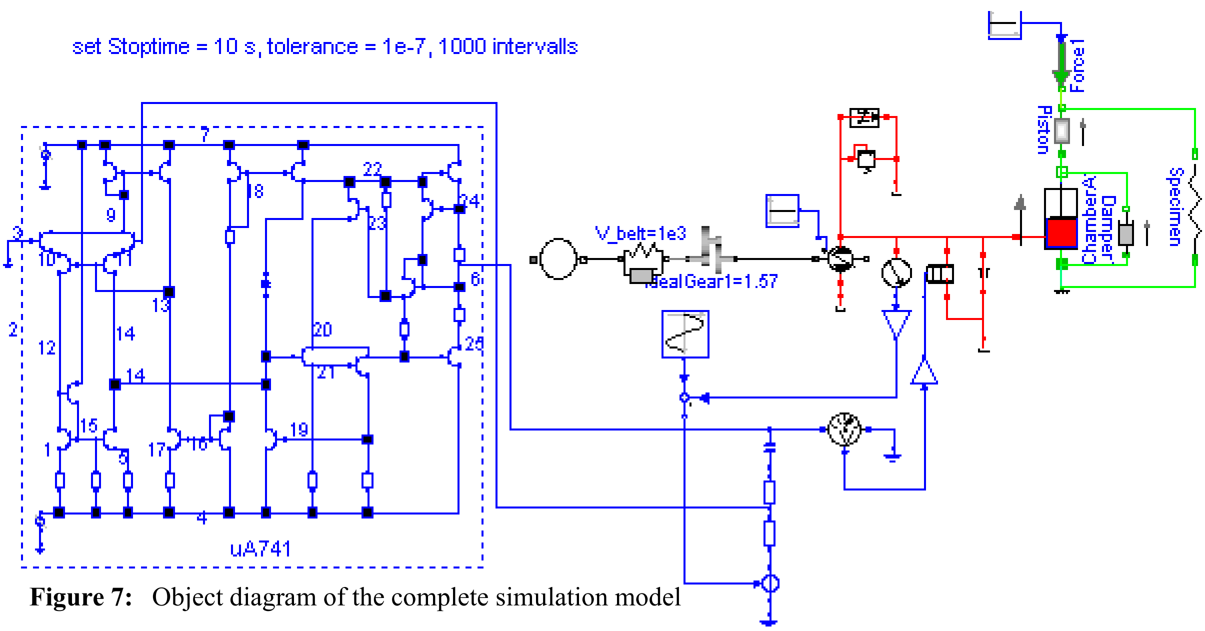

Figure 7: Object diagram of the complete simulation model

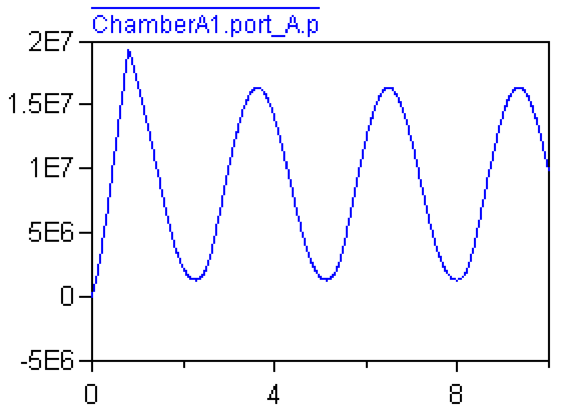

Figure 10: Pressure in the chamber

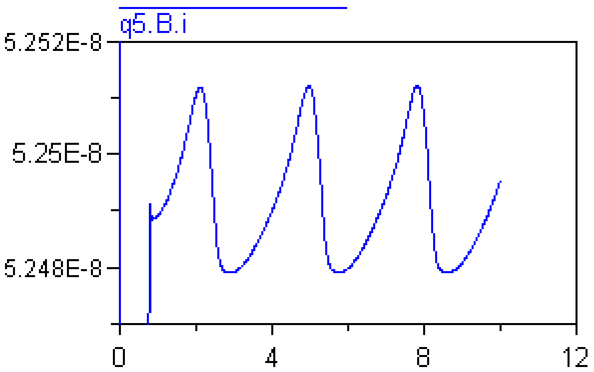

Figure 11: Base current into transistor q5

At first the Dymola tool establishes the total differential algebraic system. A symbolic calculation step reduces the number of variables/equations before the integration starts.

In the following considerations the model without electronics but with a PI-controller of the block library is used for comparisons. It will be called block model, whereas the detailed model described above will be called detailed model.

The following table compares the number of variables/equations before and after the symbolic reduction.

	Number of variables/equations	
	before reduction	**after reduction**
detailed model	1031	487
block model	309	137

Characteristical are the very different ranges of the variables. This is illustrated by the above shown pictures **fig. 8** to **fig. 11**.

The eigenvalues of the linearized system differ exceptionally: the smallest is about -4.7361e+11, the largest about -1.9441e-5. Therefore, the system is extremely stiff.

The CPU time needed depends on the tolerance of the numerical solver. If the tolerance is 1.e-7 and 1000 output intervals are specified then on a Pentium III (533 MHz) it takes the translation and linking 23 s, and the simulation 232 s. Most of the simulation time is used for leaving the quiescent state. If the stop time is 20 s the CPU time needed is only 4 s higher.

Important for an effective simulation is the optimal choice of the tolerance of the numerical solver. In the following table the statistic is compared at different tolerances for a stop time of 10 seconds and 1000 output intervals, regarding the number of successful steps, the number of F-evaluations, and the number of step events:

	Number of		
Tolerance	**succ. steps**	**F-evaluations**	**state events**
1.0e-5	-	-	-
5.0e-6	5561	253025	104
1.0e-6	6160	215790	106
1.0e-7	9821	266447	516
2.0e-8	16774	390555	145
1.2e-8	26368	938770	1509

If the tolerance is 1.e-5 the simulation time progress is very small. This table shows that the performance slows down if small tolerances are used. But it also slows down if tolerances are too large. Therefore, an optimal tolerance exists which is at about 1.e-6. In contrast with this behaviour at the block model the computational work for the block model does not increase if the tolerance becomes larger.

Consequently, the CPU times depend on the tolerance chosen. If the optimal tolereance 1.e-6 is used the CPU time of the total model is as high as the CPU time of the block model at the same tolerance. With other tolerances the CPU time of the total model is of course higher.

These results show that in multidomain examples also the difficulties of each domain come together and react together. This point of view will have to be investigated more thoroughly.

7 Conclusion

A rather complicated multidomain example could be modeled and simulated in an easy way **without** simulator coupling. Within reasonable computing times several problems of design specifications could be solved. More than thousands of variables can be handled. Both extremly stiffness and very different ranges of variables are possible.

To encourage more detailled and more easy modeling the following improvements are suggested:

- Further physical components with multidomain aspects should be offered in the Modelica standard library
- For electronic devices the support of SPICE netlists and SPICE models is necessary

To get more insight in the multidomain simulation with regard to both modeling and numerical aspects much more complex examples are desirable.

8 Acknowledgements

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