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HIL-Simulation of the Hydraulics and Mechanics of an Automatic Gearbox

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HIL-Simulation of the Hydraulics and Mechanics of an Automatic Gearbox

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Abstract

In this article, hardware-in-the-loop (HIL) simulation of a passenger car automatic gearbox is discussed. The simulation includes detailed models of the mechanics and hydraulics and less detailed models of the other parts of the car's drive train like its engine, torque converter, differential gearbox, chassis and driving resistances. After a short description of the components to be modeled, special issues of simulating variable-structure mechanical systems (coupled frictional elements), simulating hydraulics and simulating in real time with the gearbox control electronics hardware in the loop are discussed. A simulation based, detailed assessment of the dynamics of the gearbox hydraulics show that it might be modeled (under certain assumptions) with fixed causality without major loss of accuracy. Therefore nonlinear systems of equations in the hydraulic parts of the model can be avoided. This enables the usage of a model based on hydraulic component submodels, rather than on overall global dynamics to be used for real time simulations with standard HIL-simulation hardware. The article ends with a short discussion of HIL-simulation results and an outlook on future work.

1. Introduction

The motivation to realize tests in a HIL-environment is manifold, but two main reasons are:

Shorter development time. The time available for the development of new components and cars is becoming shorter and shorter. Thus, a lot of time has to be saved during the development phase. HIL-simulation and testing is a possibility to achieve this, as

- There is no need to wait for prototype production, if the data of these are available for modeling,
- No driver and test circuit is needed,
- Test conditions can be reproduced precisely,
- Tests can even be automated.

Rising complexity due to interacting electronic control systems. Cars have always been aggregations of several subsystems like engine, gearbox, brakes and so forth, and thus showed a certain complexity. But in former times those systems worked rather independently and could therefore be developed and tested separately. Nowadays the subsystems of passenger cars are strongly interdependent:

- Different control systems act on the same dynamics (e.g. both motor management (DME) and gearbox controller (EGS) influence the longitudinal dynamics (fig. 1).
- Different control systems share sensor information that is exchanged via CAN bus for control purposes, but also for self-diagnosis.
- Functions are spread over several controllers.

As a consequence systems can no longer be tested separately and the number of different error cases that have to be tested increases drastically. The test environment has to include all essential parts or functionalities of all interacting systems. Optimal testing should be automated in order to handle the number of error cases. Both requirements lead to automated HIL simulation and testing.

This article describes the test environment that was installed at BMW in order to test the control system

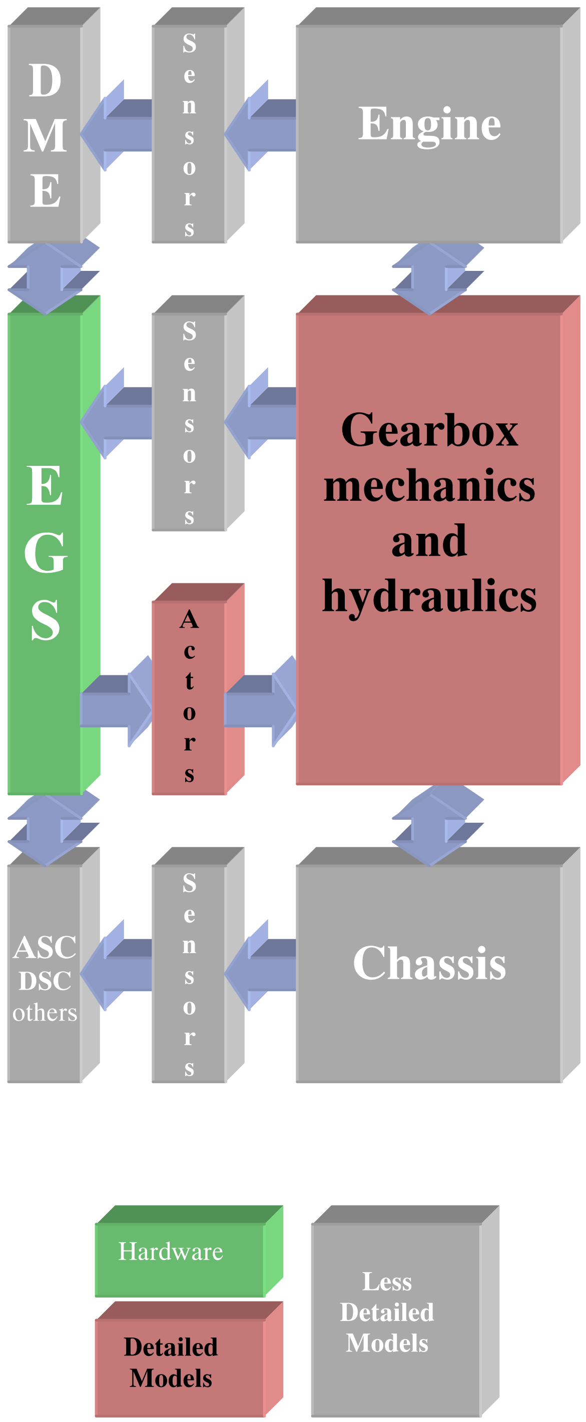

Figure 1: System overall view

(EGS) of the automatic gearbox. For the above mentioned reasons, it was not sufficient to model only the gearbox itself that is controlled by the EGS, but also the remainder of the powertrain and parts of its controllers and communication structures. Figure 1 gives an overview of the components, physical interactions and information flow:

- The EGS represents the hardware in the loop and is the item under test. All other parts are simulated.
- Gearbox mechanics, hydraulics and actuators have been modeled in detail. This was necessary, as one of the goals of this setup was the possibility to simulate the effects of failure of one of the actuators or the hydraulic valves.
- The less detailed models contain only those functionalities that are necessary for the simulation, e.g. the model of the DME does not control a full model of the engine, but is necessary to transmit the required signals via CAN bus to the EGS.

2. Modeling driveline and gearbox mechanics

An automatic gearbox can be simulated only if the input and output torques or speeds are known. Therefore, at least the engine and the longitudinal dynamics of the vehicle also have to be modeled. Figure 2 shows a corresponding model: Engine (controlled by a control unit and a driver model), torque converter, gearbox, final drive, brake wheels, vehicle inertia and driving resistances. The engine is modeled by a torque map, the torque converter by static characteristics, and all other components, apart from the gearbox, by the well known physical relations.

Figure 3 shows an outlined sketch of the 5 speed gearbox ZF 5HP24 [1] which was investigated. Apart from the hydrodynamic torque converter it consists of three planetary wheel sets and seven switching elements: Three clutches (A, B, C), three brakes (D, E, F), and a freewheel (FF). The gearshift pattern (fig. 4) indicates which switching elements have to be active to engage a certain gear.

If appropriate component models are given, the object-orientation of Modelica allows to derive the complete simulation model (fig. 5) easily from the gearbox scheme of figure 3. For the component models the standard Modelica library “Mechanics.Rotational” [2] and the Modelica powertrain library [3] have been used. For more details of modeling automatic gearbox mechanics see [4].

Clutches, brakes and freewheels in a simulation model result in a variable structure system, this is because two shafts can stick or slip relative to each

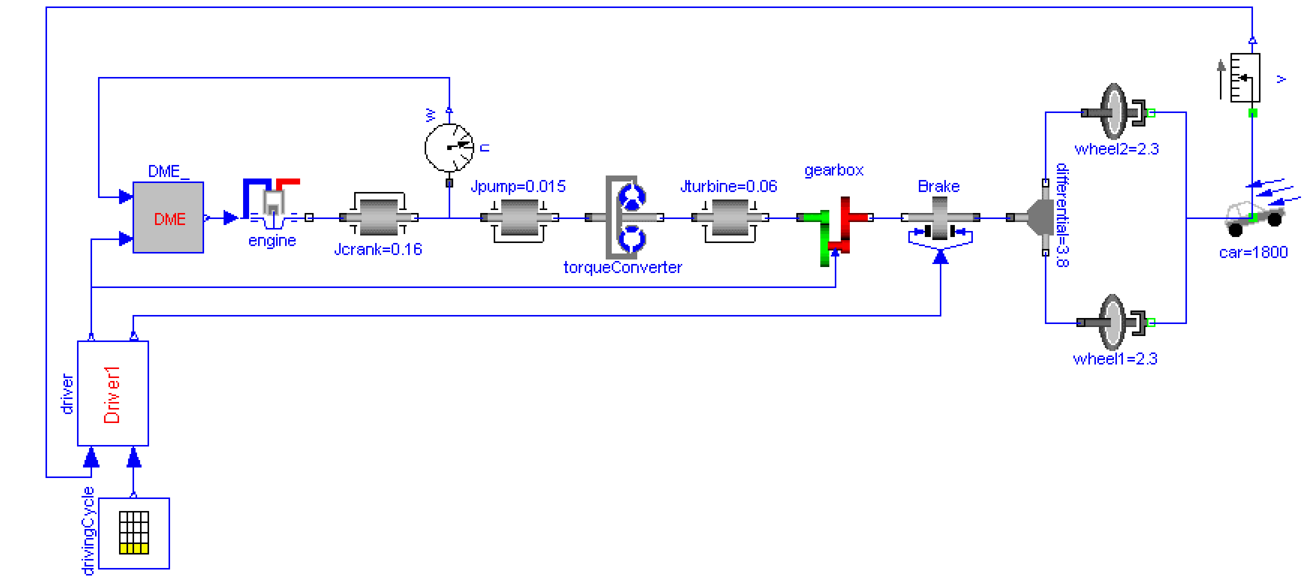

Figure 2: Drive train simulation model

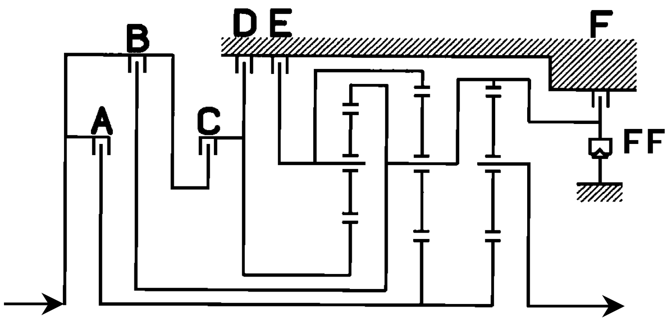

Figure 3: Outlined sketch of 5 speed automatic gearbox ZF 5HP24

Gear	A	B	C	D	E	F	FF
R			x			x	
N						x	
1	x						x
2	x				x		
3	x			x			
4	x	x					
5		x		x			

Figure 4: Gearshift pattern

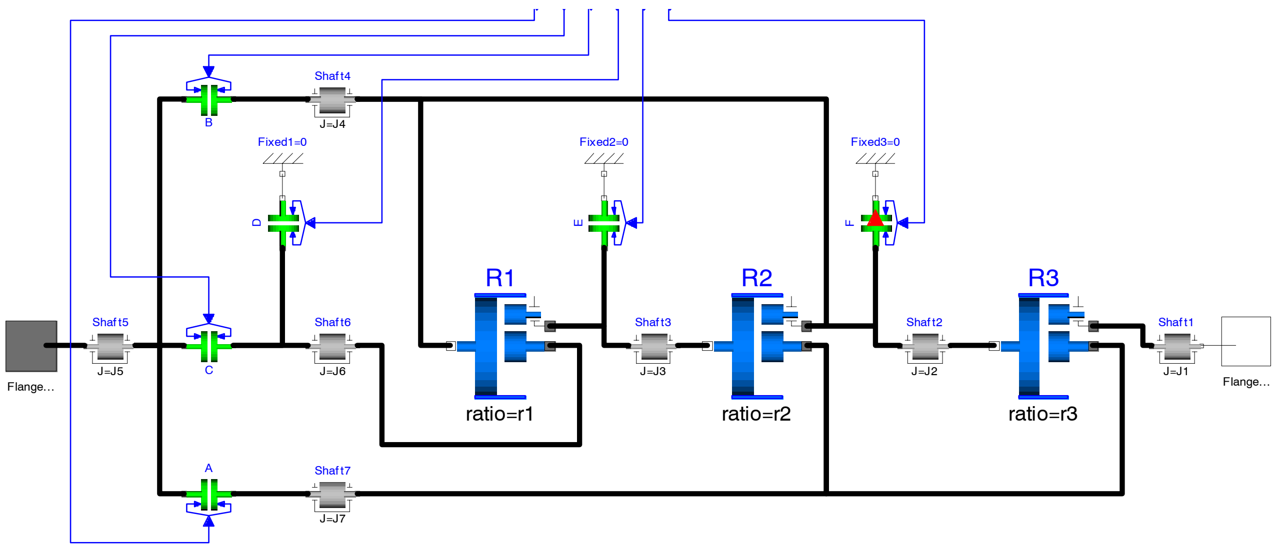

Figure 5: Gearbox mechanics simulation model

other. The number of states is changing during a transition from stick to slip and vice versa. Neglecting some “fast” dynamics in order to reduce simulation time results in a typical idealized friction characteristic shown in figure 6. The friction torque is a discontinuous and in part non-unique function of the relative speed of the clutch disks. Therefore additional equations have to be set up for a complete system description.

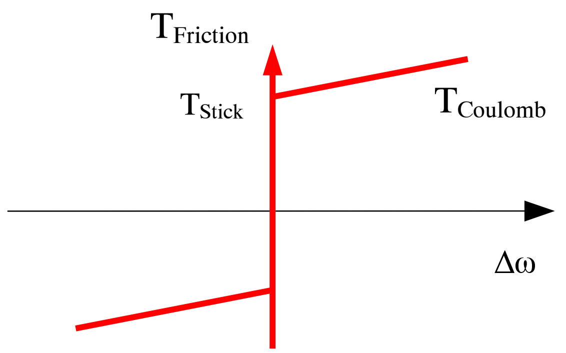

Figure 6: Idealized friction characteristic

In the Modelica libraries used, friction is modeled in a parameterized form (in contrast to [4]) with a curve parameter included plus a state machine describing the transitions between the unique and non-unique parts of the idealized friction characteristic. Because the relative speed in the clutch is an output of the integration algorithm and computed with a limited precision only, finding the transition between the unique and non-unique parts of the friction characteristic is not trivial. This holds especially for systems with several interacting clutches, like the system treated here.

Modeling a clutch by a parameterized friction description in connection with a state machine results in a mixed system of discrete and continuous equations, which cannot be solved by standard methods like Gaussian elimination. There are a few methods to solve such mixed systems [5], all of them need iteration at an event instance (transition from stuck to sliding mode and vice versa). Using Dymola [6] for processing of the Modelica models, these iterations proved to converge quite quickly. Therefore the real-time condition was met in the HIL setup with only a few exceptions.

3. Modeling gearbox hydraulics

The hydraulic system of an automatic gearbox consists of different elements with the following functions:

- Electro-hydraulic elements provide a hydraulic pressure as a function of the electrical current flowing through the element.
- Switching valves open or close canals.
- Proportional valves amplify pressures and / or transform hydraulic impedances.
- Cylinders generate a normal force on a clutch pack if a hydraulic pressure is applied on them.

Figure. 7 gives an overview over the elements and their interactions. In the following section a short outline of modeling techniques for hydraulic systems is given.

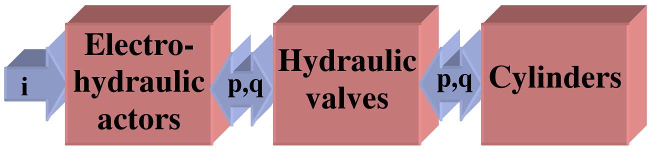

Figure 7: Interaction of hydraulic subsystems

The early simulation languages were block-oriented [7] and emulated analog computers. They were very well suited for the simulation of control systems where the output signal of a control block doesn’t influence the input. Hydraulic systems, however, work differently: The state at the input port of a component *is* dependent on the state of the output port. A hydraulic line illustrates this: If the line is closed at the end the pressure at the entrance will rise according to the input flow rate. If the line is open at the end the pressure at the input will fall almost to atmospheric pressure. These dependencies can be modeled with block-oriented software but lead to awkward models because of the necessary feedback loops. It is very difficult to build modular models with this approach.

Modelica enables *acausal* modeling, i.e. it is possible to describe the behaviour of a component without defining which variables are input and which are output variables. As a consequence it is possible to use the same library model for a hydraulic pump (input is the mechanical power, output the flow rate) and a hydraulic motor (input is the hydraulic power, output the torque at the shaft). This object oriented modeling approach thus resembles the design strategies of component manufacturers: They use (to a great extent) the same parts for pumps and motors. [8].

Hydraulic systems can be described by differential-algebraic equations (DAE). The differential equations are usually non-linear first-order equations that model the pressure build up in lumped volumes. Only special cases require partial-differential equations (PDE) to describe the behaviour of long lines. Usually these PDEs are discretized to arrive at a system of first order ODEs.

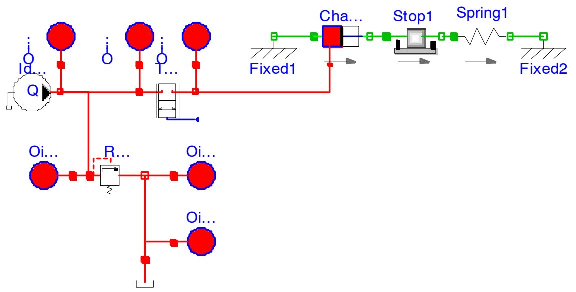

Figure 8: Modeling approach using lumped volumes.

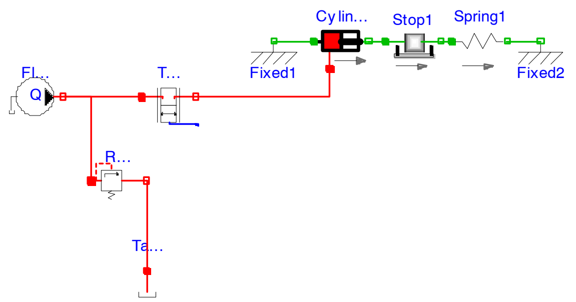

Figure 9: Library models; the lumped volumes at the ports are included but not shown in the icons.

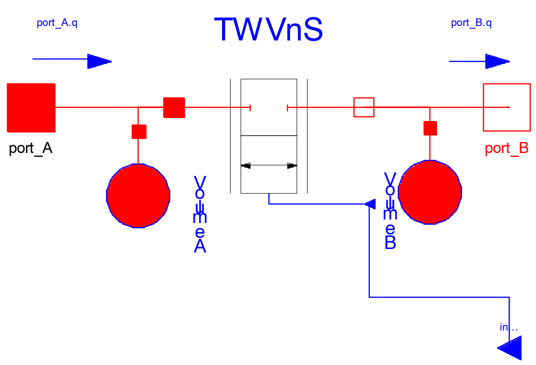

Figure 10: Diagram layer of library valve model with included volumes at the ports shows more details.

For standard applications it has proven very helpful to place a lumped volume at each port of a component to model the behaviour of the compressible oil (fig. 8). This leads to a simple structure of the resulting DAE-system. However to be able to solve this DAE with standard solvers it is necessary to reduce the index. In former times this was done by hand from the modeling engineer by adding the amount of oil of all components connected at a particular node, nowadays it can be done automatically by the tool.

To avoid the manual placement of volumes and the resulting cluttering of the diagram layer library models are available that have already included the lumped volumes at the ports but don't show them in the icons. The resulting diagram layer is almost identical to a standard hydraulic circuit diagram (fig. 9 + 10). It can therefore be read also by engineers with training in hydraulics but no deeper experience in modeling and simulation [9].

When modeling hydraulic systems it makes sense to follow the path of the oil: The source is the pump, the sink is the tank, the cylinders, motors and valves are in between. Using an appropriate library even complex circuits can be modeled in a short period of time if the required parameters of the components are known [10].

The advantages of the outlined concept are obvious. Hydraulic components can be modeled in a truly modular way. They can be arranged in an arbitrary structure – parallel or in series. The resulting nonlinear DAE system can be solved for the derivatives of the state variables thus avoiding the numerical solution of systems of nonlinear equations. There are however also some drawbacks. The lumped volumes between components can become very small, they may contain less than a thimble full of oil. As a consequence the pressure builds up very rapidly. In mathematical terms this means a *stiff system* that has eigenvalues near the origin and almost at minus infinity. Using advanced integration algorithms with automatic step size control these DAEs can be solved successfully but the required computing time will usually be greater than the simulated time. Considerations of the numerical stability will restrict the permissible step size for fixed step-size algorithms that are used for HIL simulations.

One way to reduce the required computing time is the observation that not all pressure states (lumped volumes) are significant for the overall behaviour of the model. In that case it is possible to eliminate a state. As an example figure 11 shows two orifices in series.

If the pressure dynamics of the lumped volume between the two orifices is not significant one can neglect it and assume that the flow rate through both orifices is identical. It is then possible to calculate the flow rate through both orifices as a function of the pressure differential across both orifices. This approach is identical to the assumption of a zero volume.

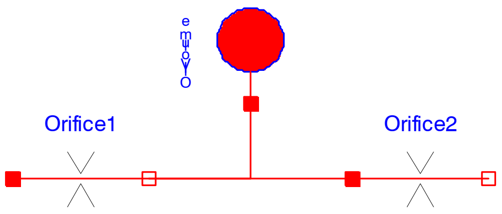

Figure 11: Two orifices in series.

In general, using these techniques, one has to find a compromise between placing a lumped volume at each connector and not using them at all. The first approach avoids nonlinear systems of equations, but generates a stiff system. The second approach does not generate a stiff system, but the resulting system of nonlinear algebraic equations has to be solved numerically. Thus, both approaches will lead to long simulation times (compared to simulated time), the optimum is a combination of both.

Unfortunately, using this method simulation times are still far from real-time using a standard HIL simulation processor (we used a Motorola PowerPC 750 processor running at 480MHz). Thus, another simplification has to be made. Detailed analysis of the hydraulic system shows that it is possible to use a causal approach for some elements: For the majority of the valves, the generated pressure of one valve can be considered to be independent of the valve that is driven by that pressure, as the volume flow of oil is usually small. Thus, a model can be derived from an acausal model where the majority of the elements is modeled in a causal way, which speeds up simulation times to an extent that real-time simulation becomes possible.

4. Gearbox electronics & HIL

After having combined all necessary simulation models (all subsystems shown in fig. 1 apart from the gearbox controller EGS), they have to be implemented on an appropriate real-time processor together with all interfaces needed. For the Modelica implementation of the gearbox mechanics model, we used Dymola and exported the processed model as a Simulink S-function [11]. The fixed causality hydraulics model and the software interfaces to the hardware have been implemented in Simulink too. Since the gearbox controller provides no trigger signal the simulated plant model has to be sampled much faster than the controller. The EGS under test operates at 100 Hz, requiring a sampling rate of 1 kHz for the simulation model. For the real-time simulation hardware we used boards by dSPACE [12].

Setting up a HIL simulation often non-standard interfaces are needed due to I/O reversal: Sensors and actuators are simulated, but they interface in part directly to the power-electronics part of the control unit which needs the respective electric loads for proper operation. In contrast, standard real-time I/O interfaces provide TTL-level signals only.

The EGS senses the speed of the gearbox input- and output shafts and oil temperature. Based on these signals (interfaced directly) and other signals like vehicle speed, throttle position, and estimated engine torque (interfaced indirectly via CAN bus), the actual gearshift is performed according to a shift map and a set of parameters adjusting the slope of the hydraulic forces acting on the respective clutch packs to the actual driveline and vehicle state. During a gearshift the EGS may require via CAN bus the engine controller to reduce engine torque for a smooth transition.

On the output side the EGS interfaces directly to electro-hydraulic components of the gearbox. The respective original parts are included in the HIL setup to provide proper electrical loads. That parts are combined in a load box which may be exchanged for simulation of another automatic gearbox type. Without proper electric loads at the power-electronics interfaces the EGS would operate in emergency mode only (4^{th} gear, no gear shift) due to implemented watchdog functions. For the same reason health monitoring signals of other controllers have to be provided via CAN bus, too.

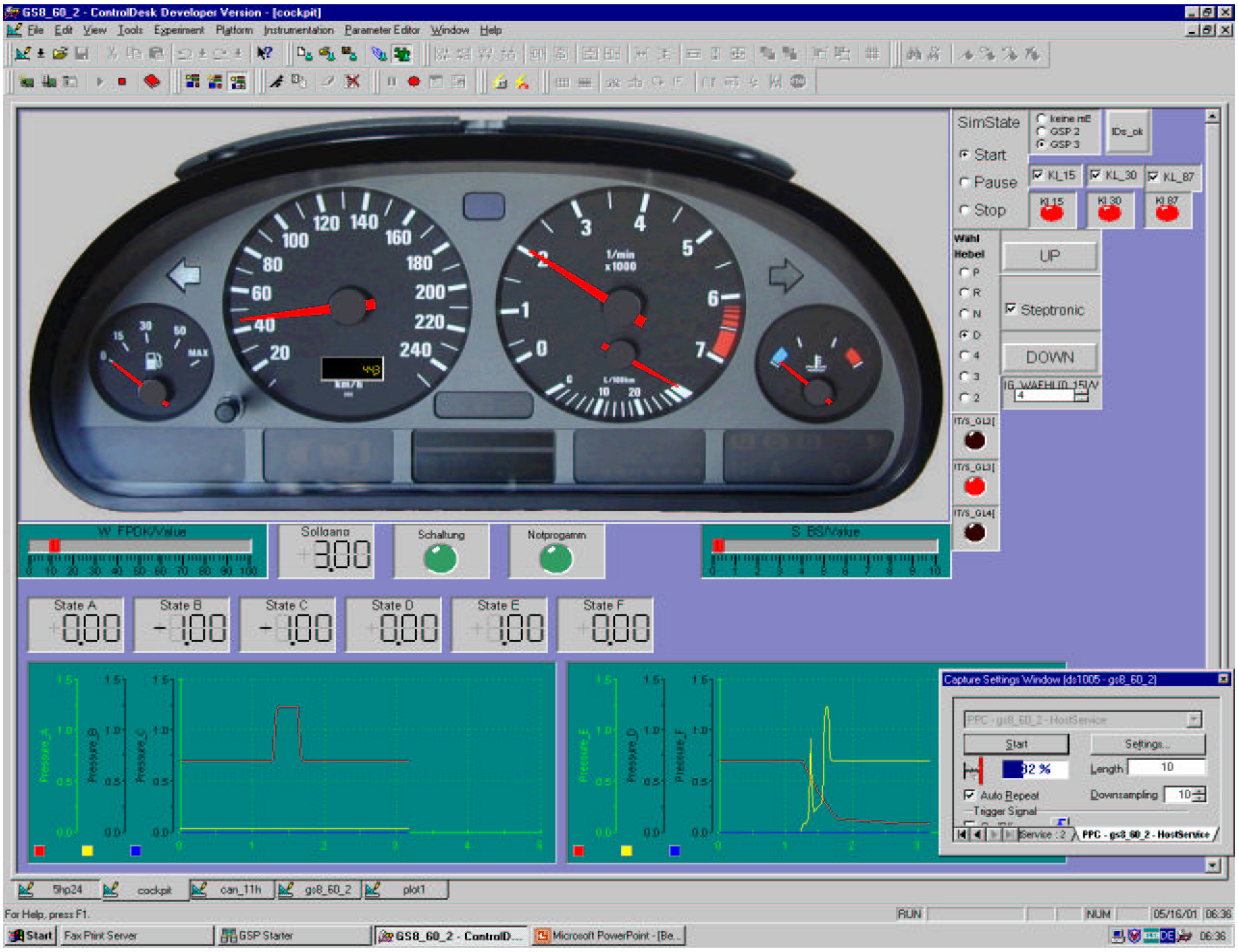

Figure 12: HIL simulation control main panel

For the operator interface to the simulation we used the board vendors software ControlDesk [12]. Figure 12 shows the main panel with standard passenger car instrumentation, gearshift control, simulation control, and simulation output of the actual state and the pressure history of all six clutches of the gearbox.

With the HIL setup described the effects of partial or total failure of one or more mechanic, electric, or hydraulic components of the gearbox can be studied in detail. For interfacing to the EGS software, e.g. for changing parameters, disabling certain parameter adaptation functionalities, etc. an additional device is needed. We used INCA [13] for that task.

5. Simulation Results

The following simulation results show the hydraulic pressure (in [N/mm^2]) for two cylinders as a result of two gear shifts. Until t = 1s, the neutral gear is engaged. Then, the first gear is engaged, and the gearbox switches to the second gear at t = 3s. Figure 13 shows the simulation results for the acausal model, simulated with Dymola. Figure 14 shows the same, but the results are based on a causal model with the same parameters.

The results for both models are fairly similar, proving the assumption to be correct for most of the time. This is not the case for the pressure in cylinder A around t=3.5 s (red circle). In the acausal, precise model, the pressure in A falls slightly, because cylinder E gets filled by a considerable volume flow. Thus, the working pressure drops, which is also reflected in the pressure in cylinder A. As it can be expected, the causal model does not show this effect.

Figure 15 shows the influence of a EGS parameter modification (application parameter). The result represents an uncomfortable gear shift, as the pressure in cylinder E shows a peak (blue circle). The fact that changes in these parameters are reflected in the pressure buildup opens the possibility to use these models for application purposes, too.

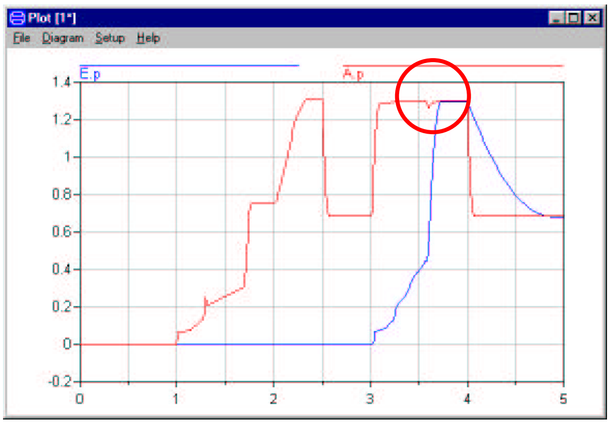

Figure 13: Simulation results: Acausal model

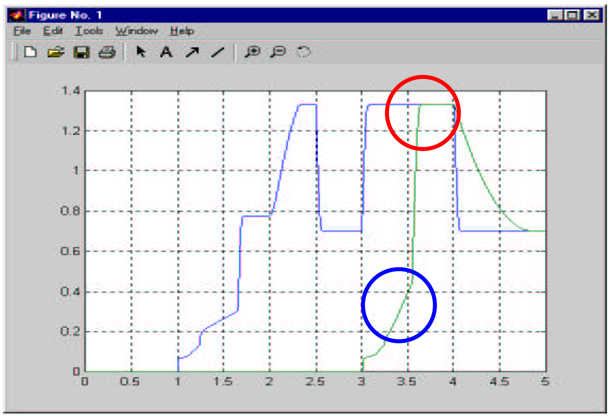

Figure 14: Simulation results: Fixed causality model

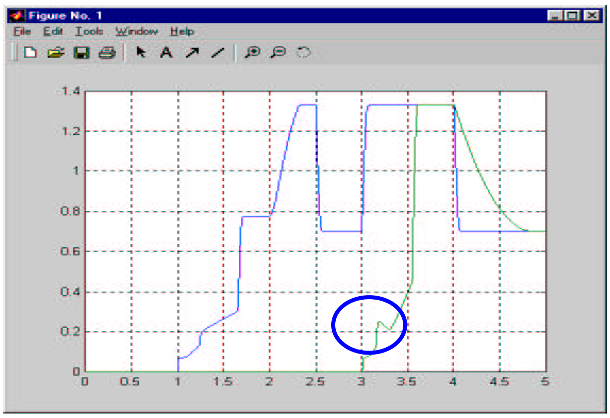

Figure 15: Simulation results: Effects of poor application parameters.

6. Conclusion & Outlook

Using the available component models of Modelica, quite detailed models of gearbox hydraulics and mechanics have been developed. Further investigation showed the possibility to model the gearbox hydraulics in part with fixed causality, which allowed real-time simulation of both hydraulics and mechanics. This model was implemented on a HIL environment together with the gearbox controller. For fully automated component failure tests of the EGS the respective models have to be enhanced by failure injection inputs.

The fixed causality hydraulics model may also be implemented in Modelica. This would enable to split up the combined mechanics and hydraulics model in “slow” and “fast” parts and thus using the potential advantage of Dymola’s inline integration scheme [14]. A limitation may be that the presumable “slow” mechanic parts of the model need “fast” sampling too, in order to meet the real-time condition if iterations occur at an event instance in the clutch models.

An other area of future investigation might be the use of simulation models for application purposes. This creates the need for further improvement of the models without loss of simulation speed. Since only a limited set of signals are available for measurement with reasonable effort, setting up procedures for identification and validation of those refined models needs to be addressed.

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