Simulation of Hydraulic Recirculating-ball Power Steering in Commercial Vehicle Models

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Kurzfassung

In Nutzfahrzeugen werden aufgrund der Leistungsdichte Blocklenkungen mit hydraulischer Servounterstützung verbaut. Um die für eine Lenkungsauslegung notwendigen Lastfälle si-mulativ darstellen zu können, ist eine Abbildung des Gesamtsystems aus dynamischem Fahrzeug und Lenksystem notwendig. Im vorliegenden Beitrag wird eine hydraulische Block-lenkung mit SimulationX modelliert und unter Verwendung der FMI-Schnittstelle mit einem SIMPACK-Fahrzeugmodell für eine Gesamtfahrzeugsimulation gekoppelt. Mit diesem Simu-lationsverbund können z.B. Fragestellungen zum Einfluss der hydraulischen Komponenten und Parameter (Ventilkennlinie, Ölversorgung, Leitungen) auf das Gesamtfahrzeugverhalten untersucht werden.

Summary

Due to their power density, recirculating-ball power steering systems with hydraulic support are installed in commercial vehicles. To simulate the loads necessary for designing the steering system, a model of the overall system comprising the dynamic vehicle and steering system is needed. In this paper, a hydraulic recirculating-ball power steering system is modeled with SimulationX and, using the FMI, coupled with a SIMPACK vehicle model to create a simulation of the overall vehicle. This integrated simulation enables to analyze, for example, the influence of hydraulic components and parameters (valve characteristic, oil feed, hoses) on the overall vehicle behavior.

Introduction

For driving dynamics calculations with the overall vehicle, not only does the mechanical function have to be modeled, but also the steering system. For reasons of calculation speed, the steering has so far been modeled using a simplified, massless system that calculates torque equilibrium in the steering gear and contains only a few hydraulic parameters. But to support steering system design with an overall vehicle model, a detailed model of the steering system is required.

A simulation like this can be realized through various approaches: By programming user-specific hydraulic elements as an extension of the mechanical model in the multi-body simulation program [1]; by coupling mechanical and hydraulic subsystem models using two different simulation programs [2]; or by using simulation programs that allow both the mechanical and hydraulic domains to be modeled [3],[4].

If, when modeling the subsystems, you do not want to forget the benefits of software specially tailored for a single domain, the mechanical and hydraulic subsystems have to be coupled. The industrial use of this kind of coupling requires the use of "standard interfaces" supported by as many software manufacturers as possible because proprietary interfaces require a high level of in-house development and maintenance work. The FMI [9],[11] (functional mock-up interface) for coupling models and simulation tools has the potential to become just such a standard interface. This paper describes the coupling, developed as part of a diploma thesis and using the FMI, of a coach model created in the SIMPACK multi-body simulation program and of a servo-hydraulic ball-and-nut steering gear, modeled in SimulationX.

The Recirculating-ball Power Steering System – Steering in Commercial Vehicles

The task of the steering system in motor vehicles is today realized through two different steering gear concepts: rack-and-pinion steering and ball-and-nut steering. The former concept is mainly employed in passenger cars due to its cost-effective and low-weight design and because it requires little installation space. The latter concept, which is the subject of this paper and is also known as recirculating-ball power steering due to its design, has become established in the commercial vehicle sector thanks to its robustness, compact design and high power density [5], [6], [7].

Figure 1 shows a schematic diagram of a hydraulically assisted ball-and-nut steering gear.

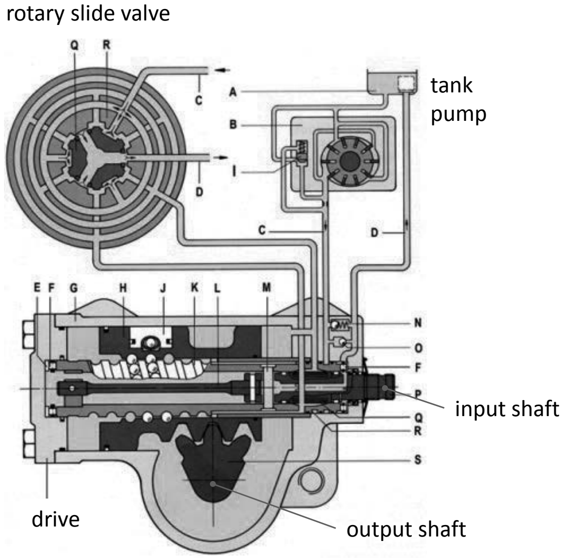


Figure 1: Ball-and-nut-type steering gear with hydraulic assistance [8]

The steering movement from the driver is transferred to the transmission via the input shaft. In the transmission, the ball circuit in the steering nut (K) converts the rotary input movement to a translational movement of the steering nut (H). This is assisted by hydraulic means and translated, in turn, into a rotary movement of the output shaft by a sector gear. The pitman arm (not shown) then transmits the movements on to the steering linkage (see Figure 2) [5].

The hydraulic components of the system include the pump (B) and tank (A) in the rear of the vehicle (bus), the supply line to the front of the vehicle (C, D) and the rotary slide valve (Q, R). As a central component of the hydraulics, the latter controls the volume flows and ensures that pressure builds up in the hydraulic chambers and, in turn, that servo power builds up on the steering nut depending on the steering movement from the driver [8]. The valve opens due to relative rotation in the torsion bar (L), whereby once a mechanical end stop has been reached, the input shaft torques are transmitted directly to the ball circuit in the steering nut.

The Overall Vehicle Model of the Coach

The SIMPACK multi-body simulation software is used for driving dynamics calculations. It allows the computer-based analysis of mechanical systems that can be described by rigid or elastic bodies. The actions of forces between these bodies can be defined (e.g. the suspension systems or tires). Figure 2 shows the modeled bus and an enlarged view of the front axle with steering kinematics and recirculating-ball power steering.

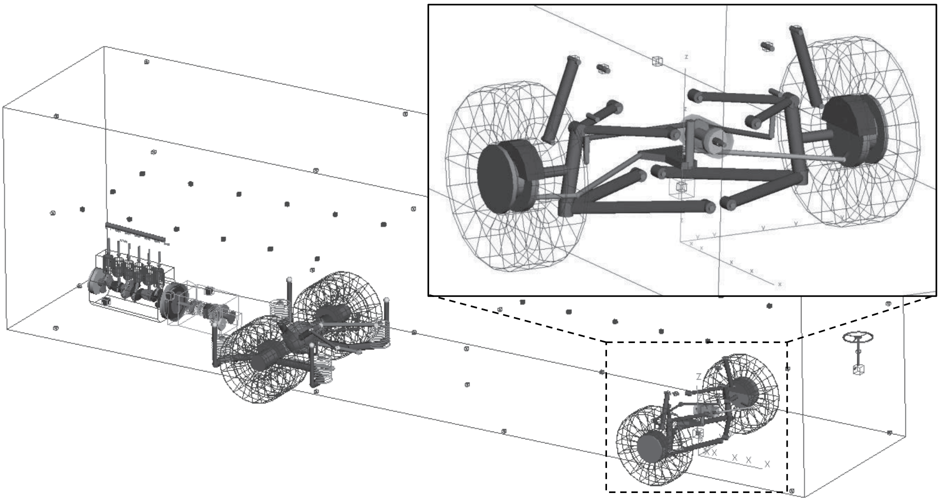


Figure 2: Overall vehicle model of the coach

Modeling the Recirculating-ball Power Steering

As indicated by the description of the functioning of recirculating-ball power steering, a mechanical and a hydraulic subsystem has to be modeled. Since SimulationX can also model mechanical components, the model can be created in two different ways: Either by including the complete steering system in SimulationX, or by modeling the mechanical structure in SIMPACK and the hydraulic function in SimulationX. These variants are illustrated in Figure 3. Depending on which method is chosen, different input and output variables have to be defined for communication between the subsystems.

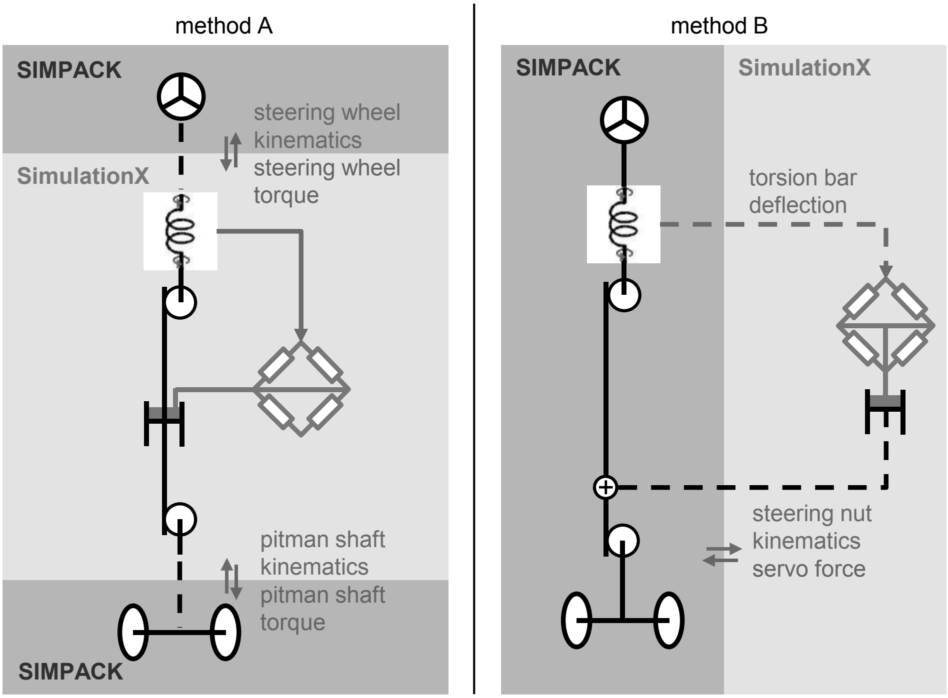


Figure 3: *Modeling methods for simulation coupling*

In method A, the entire steering gear is modeled in SimulationX. With this coupling approach, the steering gear model requires the angle and angular speed data of the steering wheel and pitman shaft from the vehicle model. From this, the torques on the steering wheel and pitman shaft are calculated and returned.

In method B, only the hydraulic section of the recirculating-ball power steering model is included in SimulationX. The mechanical components of the transmission are modeled in SIMPACK. Here, the number of variables to be transferred during coupling falls from six to four. The only output variable of the hydraulic system remains the servo power introduced into the mechanical system in SIMPACK.

Following a series of analyses using both approaches, method B has been chosen as the final model structure. The reduced number of variables to be transferred reduces the error-proneness of the simulation coupling and simplifies model design on both sides of the interface. Furthermore, a clear separation of the mechanical (SIMPACK) and hydraulic (SimulationX) systems makes it easier to analyze errors in case the system behavior is faulty.

Modeling the Mechanical Subsystem of Recirculating-ball Power Steering

The mechanical section of the recirculating-ball power steering is modeled in the multi-body simulation system as the "steering" substructure, which also contains the steering wheel and the steering cardan joint. The advantage here is that, in the subsequent analyses, the steering can be easily integrated in different test benches or vehicle models. The model also takes into account the losses in the transmission assembly and models the interface for integrating the hydraulic model from SimulationX. This is shown in Figure 4.

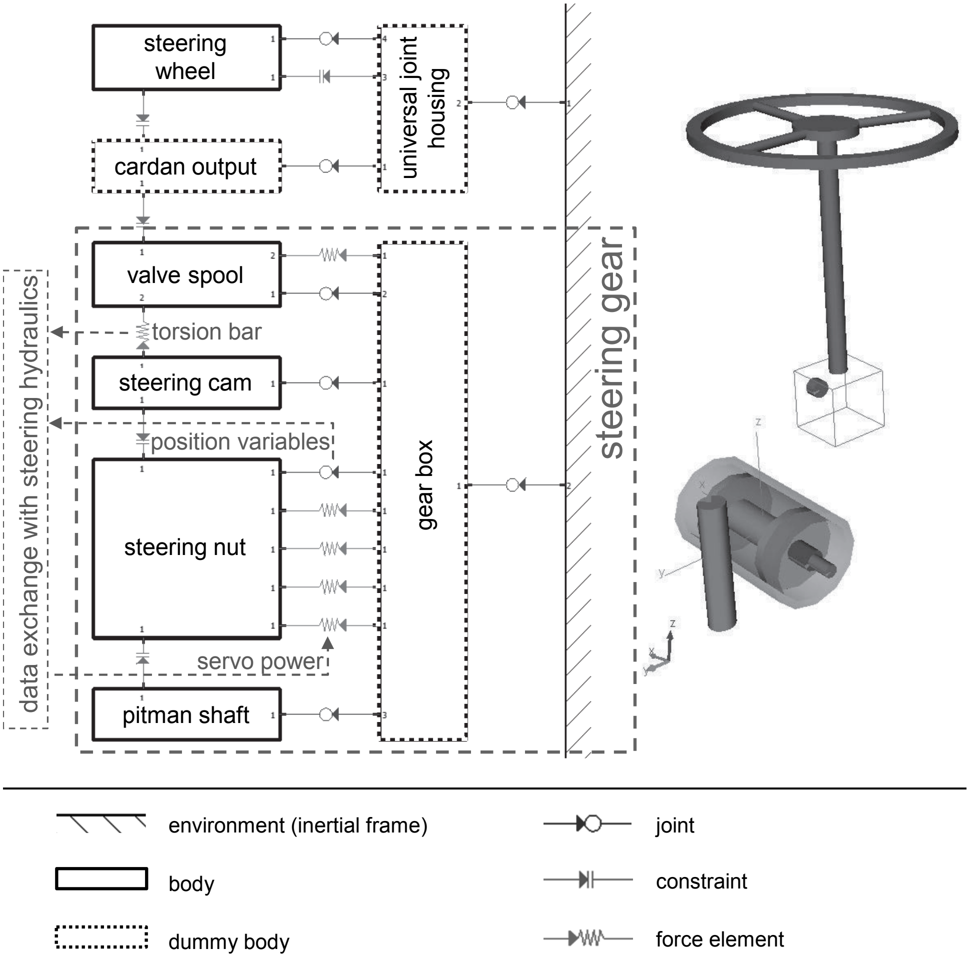
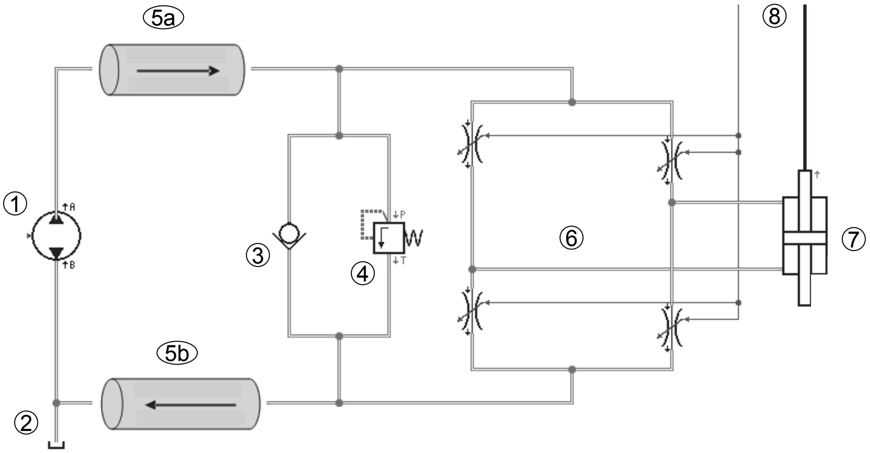


Figure 4: Two- and three-dimensional diagram of the steering model in SIMPACK

Modeling the Hydraulic Subsystem of Recirculating-ball Power Steering

The hydraulic model of recirculating-ball power steering in SimulationX is shown in Figure 5. The rotary slide valve is described via an equivalent model in the form of a Wheatstone bridge (6). The parallel flow paths distributed radially over the cross-section are each combined to form a single flow path. The supply lines are defined in separate substructures. The two valves (3,4) protect the system in case of overload and/or if the hydraulics fail.

To influence the hydraulic system behavior in a targeted manner in the subsequent design process, certain system parameters are made available externally as model parameters. These can be transferred during model coupling to the cooperating software, which means that the hydraulics model can still be parameterized even after it has been imported. These variables include the parameters for the Wheatstone bridge, the delivery volume flow of the pump and the initial temperature of the fluid.



1	servo pump	4	pressure control valve	6	Wheatstone bridge
2	tank	5a	lines (pump - drive)	7	steering nut
3	suction valve	5b	lines (drive - reservoir)	8	interface to mechanics

Figure 5: Hydraulic model section of recirculating-ball power steering

Parameterization Process

The transmission manufacturer has the valve characteristic, the data on the pressure supply and limitation as well as the torsion bar spring stiffness. The valve characteristic is established by rotating the input shaft when the output shaft is blocked, which results in an angular difference in the torsion bar and thus in a definable steering wheel torque characteristic. For parameterization purposes, this characteristic is approached by adjusting the relevant parameters in the Wheatstone bridge, whereby different parameters affect different system properties. A theoretical cross-sectional area for the neutral position determines, for example, the no-load current of the valve and resulting pressure characteristics. Parameters such as the theoretical valve radius, theoretical groove length and flow value characterize the curve.

Realizing the Model Coupling

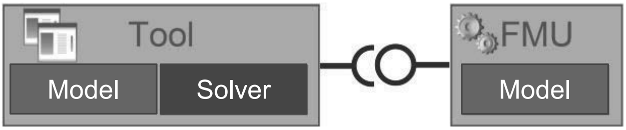
FMI – Model Coupling Interface

One of the challenges with simulation technology today is to harmonize the numerous different CAE applications currently used by suppliers and manufacturers. This is necessary to ensure that increasingly complex systems can still be simulated, on a work-sharing basis, efficiently, effectively and without compromising system knowledge by coupling models and tools. The functional mock-up interface (FMI) confronts this challenge [11].

As part of the ITEA2 project Modelisar (2008-2011), and at the initiative of Dassault Systèmes and Daimler AG, the FMI was specified, implemented for different tools and tested with numerous use cases [10]. Since this project was completed, the FMI is maintained and enhanced as part of the Modelica Association Project (MAP) [9].

FMI allows models and simulation tools to be coupled with each other on the basis of an independent, standardized interface. Two versions of the FMI are available: One for model exchange for integrating submodels in a monolithic general system, and one for co-simulation for coupling submodels that are each solved with a separate solver and coordinated via a higher-level co-simulation controller. Figure 6 shows a comparison of the two FMI variants. The exchange object in both cases is an "FMU file", a compressed data container whose content varies accordingly [9].

FMI for Model Exchange:



FMI for Co-Simulation:

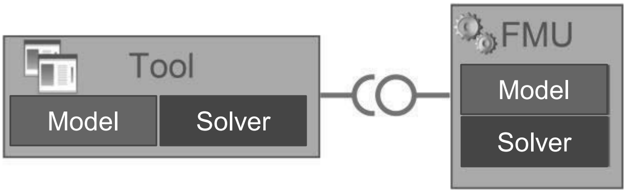


Figure 6: Comparison of model exchange and co-simulation [9]

In the case of FMI for model exchange, a DLL is generated on the basis of the C code of the model in which the system under analysis is described by its differential equations. In this case, the integrator in the target system that imports the C code solves these differential equations.

In the case of FMI for co-simulation, however, the solver of the original program is exported in addition to the differential equations of the physical system. During simulation, data is exchanged between the systems in defined time steps. Between the time steps, the systems are calculated independently of each other by their own integrators.

Realizing the Coupling of the Mechanical and Hydraulic System

When it came to the coupling of the submodels of the recirculating-ball power steering, both FMI methods were analyzed. In the diploma project, efficient, robust and sensible simulation results could only be achieved for co-simulation. When the model exchange method was used, problems arose with the switch functions in the hydraulic subsystem, although this could not be analyzed further in the limited period available for the diploma project.

Results

The following section presents the results of two driving maneuvers as representative of the analyses on the overall vehicle. In each case, the influence of different pump volume flows on system behavior was analyzed.

Stationary driving in a circle (the vehicle is continuously accelerated on a constant path radius) is a typical driving dynamics maneuver used for analyzing a vehicle's self-steering characteristics (understeer/neutral/oversteer). In the process of designing the steering system, it can provide information on the steering forces required at high lateral acceleration. Figure 7 shows the steering wheel torque characteristic over lateral acceleration for two different volume flows. A clear reduction in the steering wheel torque for a larger volume flow can be seen. This is due to the higher pressure level in the system resulting from the larger volume flow.

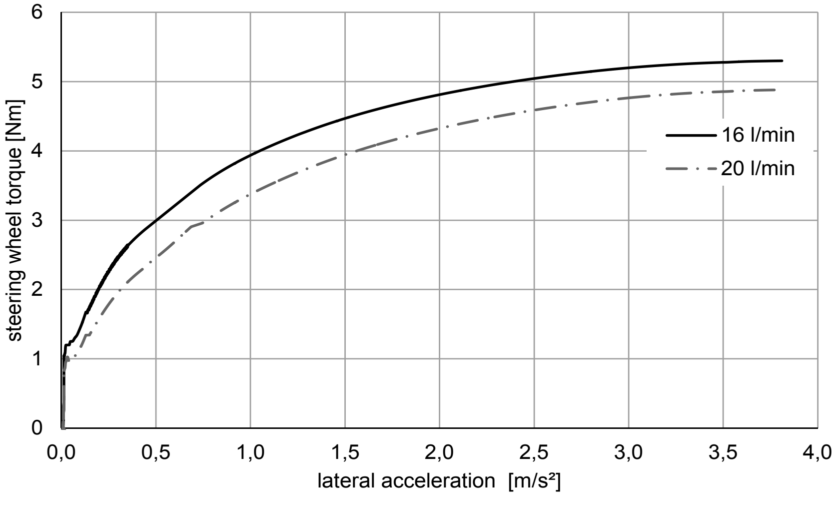


Figure 7: Steering wheel torque characteristic over lateral acceleration for different volume flows

Summary

To support steering system design by computer-aided analysis, an existing overall vehicle model of a coach was expanded to include a detailed model of a steering system. This allows different hydraulic parameters to be accessed and altered as required. Following detailed analysis, the steering system was modeled separately: the mechanical subsystem in the SIMPACK multi-body simulation environment and the hydraulic subsystem in the Modelica-based SimulationX simulation environment. Coupling of the two simulation models was realized on the basis of the FMI by integrating the exported hydraulic system with its own integrator. The results presented here highlight the effectiveness of simulation coupling via the FMI for co-simulation. They represent just the beginning of the system's application as a tool for supporting steering system design and offer potential for a wide range of further detailed analyses.

References

[1] DRONKA, SVEN Zur Einbindung hydraulischer Elemente in SIMPACK [The integration of hydraulic elements in SIMPACK] SIMPACK-News 2, No. 2, p 7-9, 1997

[2] DRONKA, SVEN Die Simulation gekoppelter Mehrkörper- und Hydraulikmodelle mit Erweiterung für Echtzeitsimulation [The simulation of coupled multi-body and hydraulic models with enhancement for real-time simulation] Dissertation, Shaker Verlag GmbH, Aachen, 2004

[3] 02.09.2013 http://www.3ds.com/products-services/catia/portfolio/dymola

[4] 02.09.2013 http://www.iti.de/simulationx

[5] MURRENHOFF, H.,GIES, S. Fluidtechnik für mobile Anwendungen [Fluid technology for mobile applications] Lecture transcript 'Fluidtechnik für mobile Anwendungen' [Fluid technology for mobile applications] Shaker Verlag GmbH, Aachen, 4th edition, 2008

[6] GEBHARDT, N. Fluidtechnik in Kraftfahrzeugen [Fluid technology in motor vehicles] Springer-Verlag, Berlin, Heidelberg, 2010

[7] PFEFFER, P.,HARRER, M.Lenkungshandbuch Lenksysteme, Lenkgefühl, Fahrdynamik von Kraftfahrzeugen [Steering manual: steering systems, steering feel, driving dynamics of motor vehicles] Vieweg+Teubner Verlag / Springer Fachmedien Wiesbaden GmbH, Wiesbaden, 1st edition, 2011

[8] 22.11.2012 http://www truckfocus.pl

[9] 17.01.2013 https://www.fmi-standard.org

[10] ABEL, A., BLOCHWITZ, T., EICHBERGER, A., HAMANN, P., REIN, U. Functional Mock-up Interface in Mechatronic Gearshift Simulation for Commercial Vehicles, Proceedings of the 9th International MODELICA Conference, 2012, Munich, Germany, 2012, 775-780

[11] BLOCHWITZ, T., NEIDHOLD, T., OTTER, M., ARNOLD, M., BAUSCH, C., MONTEIRO, M., CLAUS, C., WOLF, S., ELMQUIST, H., OLSSON, H., JUNGHANNS, A., MAUSS, J., NEUMERKEL, D., PEETZ, J. The Functional Mock-Up Interface, Modelica Confererence 2011, Dresden