Overview about the Recent Developments for Combined Control System and Mechanics Simulation in Automotive and Railway Engineering

“Simulation: An Essential Tool for Risk Management in Industrial Product Development”
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Abstract

Due to the extensive usage of active systems in the **automotive industry**, the demands on multi-body simulation (MBS) are continually increasing. The design of active systems such as ESP or damping control requires maximum flexibility for the combined simulation of control and mechanical systems - in terms of software technology, price and communication between the involved companies.

The ongoing implementation of comparably advanced technology in today’s railway vehicles and the increasing demands in ride comfort and safety create according requirements of the **railway industry**. Systems like tilting control, de-central drives and traction control make it necessary to have a close interaction between mechanical multi-body and control simulation.

In today’s industry praxis, for the mechanical dynamics multi-body systems (MBS) are used, for the control system so-called computer aided control system engineering (CACE) tools. As for most of the applications, there is no satisfying solution for the simulation of the entire system in one software tool, the interfacing of the specialised tools becomes essential. Different aspects of the interfacing, e.g. equation exchange and co-simulation are discussed.
Parallel to this off-line simulation, the creation of real-time simulation models (HIL) is a requirement. According models are running on HIL hardware to represent the vehicles behaviour for the testing of electronic controller units (ECUs) and have special requirements on the calculation performance and the structure of the equations. These real-time models should as much as possible be automatically derived from standard models. The relevant technical and commercial approaches are discussed here.

Examples out of the industrial practise are given for each method. New commercial and technical approaches are discussed for MBS-CACE interfaces which reduce software license costs for the vehicle manufacturer and which support intensive collaboration between vehicle control and dynamics experts. Additionally a new method for a process safe creation of multi-body HIL-models is presented.

1. State-of-the-Art Multi-body Models

1.2. Automotive

Today’s leading technology automotive companies use multi-body simulation in the fields of handling, ride (i.e. ride comfort and vibration effects), durability and design of control systems.

Models used for the design of typical ride dynamics control systems need to cover the frequency range of the relevant control system. As an example, handling models will be used for the design of a ESP system and ride models for an adaptive damper control system. As typical multi-body simulation tools have limited modelling functionality for control and fluid systems, advanced interfaces to specialised tools, such as MATLAB Simulink, are important. The existing interface concepts are model exchange (runtime or code) and co-simulation.

During the last few years, parallel to the offline design of mechatronic systems, the pre-prototype testing of real controller devices with the help of real-time simulation models has become a crucial point in the development process (HIL – hardware in the loop). For HIL simulations, the software tools must be able to export their models as code (mainly C-code). The code will be compiled directly on the operating system of the realtime hardware environment.

The need to test the on-board controller code also in a pre-prototype phase leads to the requirement of SIL (software in the loop) simulations, whereas this code is used in the off-line simulation environment. Unlike HIL simulations, SIL simulations no not have to run in realtime.

Limitations, open Issues
Due to real-time simulation criteria, the simulation models must be extremely efficient. In addition they must abandon differential-algebraic equations (DAE) which are usually used for automotive multi-body simulation in tools such as SIMPACK, for under real-time conditions, ordinary differential equations (ODE) show better behaviour: For the iterative solution of the algebraic equations (“constraints”) a number of iterative steps is required which can not be determined before the start of the calculation and therefore would lead to unpredictable simulation times.
For these reasons, the current state-of-the-art HIL-models are completely re-engineered in specialised tools. Normally they do not have common data sources with other types of models.

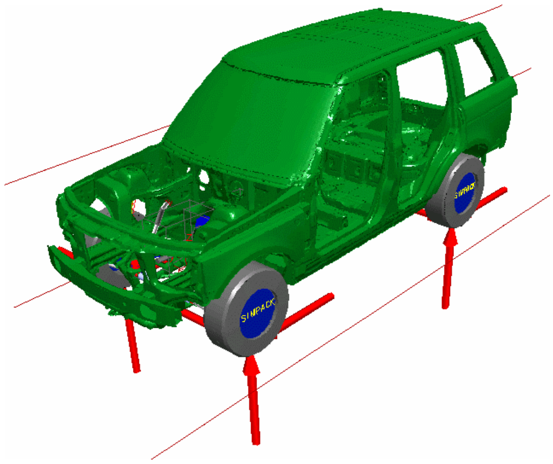

Fig. 1: State-of-the-Art Automotive Multi-body Model (SIMPACK), Picture by Courtesy of Land Rover

1.2. Railway

In the railway area similar scenarios of product development exist. However, due to the relatively high computation effort of the contact between wheel and rail and the accordingly higher calculation times, HIL simulation, which has to fulfil the realtime requirement, until now is less established in the railway area.

Limitations, open Issues
Due to this high calculation effort for the 3D wheel-rail contact and the strong interaction between lateral, vertical and longitudinal dynamics of railway vehicles, HIL applications are currently restricted to a limited range of applications, where the simulation scenario can be simplified to a 1D situation. Traction controllers are sometimes simulated with this simplification of the mechanics.
SIL simulations, however, are widely used to optimise controller code by running them in offline MBS models [4].

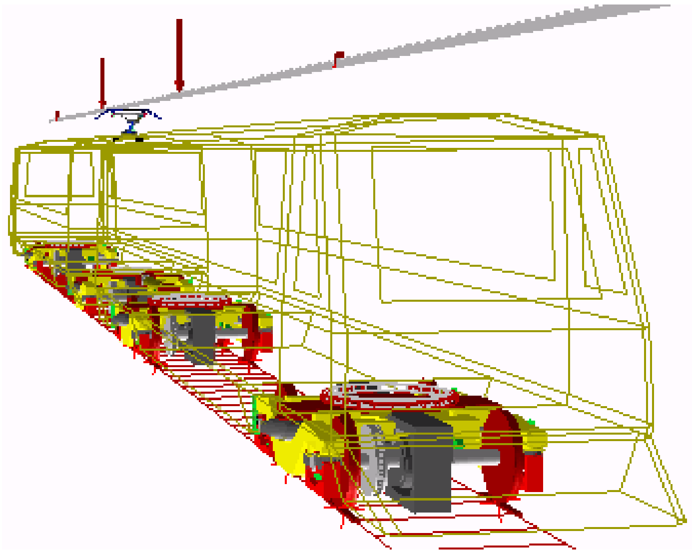

Fig. 2: State-of-the-Art Railway Multi-body Model (SIMPACK), Picture by Courtesy of Metro Madrid

2. Simulation Technologies Used for Combined Multi-body and Control System Simulation

2.1. Co-Simulation

When using co-simulation, both solvers, the multi-body system and the control system solver run and exchange data with a mostly fixed sample rate.
The advantages of this method are:

- Both system types are solved with respectively optimised numerical methods.
- The communication effort between the different software products is limited to a minimum which, as a matter of experience, decreases the maintenance effort.

The disadvantages are that

- the entire equation system may become instable when the data exchange time steps are too big
- or become inefficient when the time steps are to small.

The software tools currently on the market require full licenses of the particular products when using co-simulation interfaces.
Co-Simulation can basically be used under HIL requirements, however, for the reasons mentioned above, the mechanical equations must be available as ordinary differential equations (ODE).

2.2. Equation Export as Code

Using this method, the multi-body or control software exports its equations in symbolic form as code from the slave to the master software. The master software solves the entire system. The code gets linked and compiled and can be used similarly to a native element in the other software. With e.g. the code export interface between Matlab Simulink and SIMPACK (MATSIM; SIMPACK is master, MATLAB is slave) the parameters of the Simulink model can be accessed directly from within the SIMPACK model.
The advantages of this method are:

- Instability problems of co-simulation as described in 2.1 are not possible.
- Once the structure of the slave model is fixed, the user can access the system parameters from within the master software.

The disadvantages are that

- the solver of one tool may not be optimised towards the numerical structure of the equations of the other. This especially makes problems when railway vehicle models are exported to the CACE tool, for advanced solving methods for the wheel-rail contact are required.
- Compared to co-simulation a relatively high effort must be invested in export and compilation of the equations.

In a next step the code of the entire system can be exported to a realtime environment [2]. This method is widely used in automotive companies to create realtime models.

For SIL simulation this methods works in the very same way. The real controller code which is later used directly in the vehicle, is tested and validated within the MBS simulation model.

As the code export functionality of the software tools transfers to the user the unlimited access to all the know-how available in the software, the according prices are usually accordingly high.

2.3. Equation export at Runtime

With this simulation method one tool provides at runtime the equations for the other one. Both simulation tools are normally installed on one and the same computer. This method does not offer significant advantages to the export of equations as code, but as a matter of experience, creates higher maintenance effort, mainly if new versions of the involved software tools are installed.
Equation export at runtime practically does not support access to HIL simulation, for the extensive simulation packages do not run on the reduced realtime operating systems.
For these reasons equation export at runtime currently is vanishing from the companies simulation concepts.

3. New Approaches

3.1. A Cost Efficient Approach to Provide Multi-body Models for Offline Simulation by Code Export

In industrial practise, mechanical models of the vehicles with reduced complexity are transferred to the control system engineer's simulation platform. The models represent the vehicle's dynamics in the desired frequency range. They show a fixed model structure, as the suspension layout is already defined in this stage of the development, but must be supplied with variable parameters such as body mass, spring stiffness, damper functions, etc.
A model description as code (Fortran or C) with a defined number of multi-body library elements, but an open, user-editable list of parameters fulfils these requirements. This enables the software manufacturers to offer a subset of the entire program libraries to be exported at a cost effective price. SIMPACK provides this subset as Fortran Code for the model description itself, and binary licensed library elements for use within the model.
This approach also supports the protection of know-how and sensitive data, when vehicle manufacturers and suppliers are collaborating within the development of, for instance, an ESP system. The OEM can easily provide suspension and entire car models, whilst protecting the entire parameter set or parts of it. The supplier can use these fully functional models to optimise the ESP system.

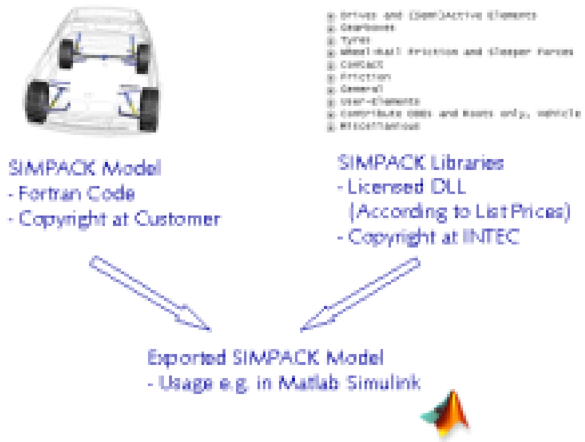

Fig. 3: Providing Multi-body Models for Control System Design Tools

3.2. A Cost Efficient Approach to Provide Multi-body Models for Offline Simulation by Co-Simulation

As discussed in 2, especially with numerically critical models, the equation export is sometimes limited by the requirements on the solver. It might therefore be desired that each system can be solved with its accordingly optimised numerics by co-simulation.
Such an approach is offered by the new interface SIMPACK&go. Again the model is exported with just the modelling elements that are required, however, unlike the code export based strategy of 3.1, the solver of the mechanical system is exported to Matlab Simulink as well. In Simulink the mechanical model is then added by internal co-simulation.
This approach is well known from the technology point of view, but due to the fact that with SIMPACK&go not the entire MBS simulation environment, but just the subset that is desired by the user is made available to MATLAB, a more attractive price can be offered.
When the providing the model data in binary form, the collaboration approach described in 3.1 can be transferred to SIMPACK&go as well.

3.3. A new Approach to Eliminate DAEs from Suspension Models for HIL Simulation

The process described in 3.1 could easily be extended towards HIL simulation, if the licensed DLLs were provided for the appropriate HIL platforms and operating systems, or if the DLLs were delivered as source code to be compiled on the HIL system. However, as described above, the differential algebraic equations that are used in offline multi-body simulation, must be eliminated.
The approach to eliminate such DAEs from MBS models, which is currently mostly used, is the storage of the equation in a multi-dimensional function array. The according functions are computed in precedent off-line simulations. The disadvantage of this method is that for each parameter change, even for minor changes, the pre-calculation of the function array and its transfer to the HIL model have to be repeated.
A more efficient approach can be achieved when solving the algebraic equations of the DAE system on position and velocity level, creating the sum of both equations and adding the resulting ordinary differential equation to the set of ODEs of the system [1].

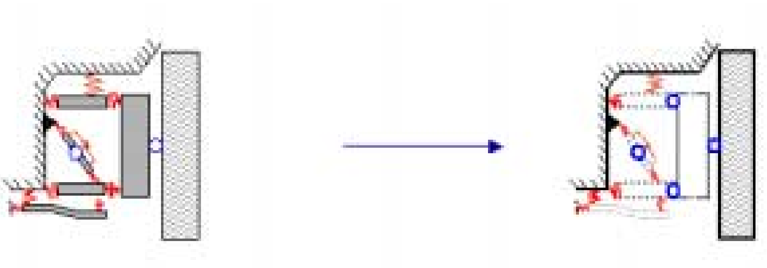

Fig. 4: Removing DAEs from the Multi-body Suspension Models

This allows a fully parameterised, but DAE-free description of the suspension in the HIL world. The parameter files of the offline simulation world can still be used, decreasing strongly the risk of supplying the HIL model with wrong or out-dated parameters.

4. Application Examples

4.1 A Car Supplier's Development Tool for Control Systems

Commonly control systems for riding dynamics in cars and more and more also in trains are delivered by suppliers. The design of such tools, however, requires models of the mechanics of the vehicles. In industry's praxis the according MBS models are created by the supplier himself.

The control system engineer is focussing on the control software environment and gets provided with ready-to-use, parameterised multi-body models from colleagues of other departments. The danger that these models underlay unwanted changes by the user must be minimised and their handling must be as simple as possible. On the other hand, a pre-specified parameter set must be open for modification.

The number of installations of such control work places reaches some multiples of ten in according companies. It is unacceptable for the companies that full licenses of the MBS tool are required for this application. In the past therefore according models have been re-programmed from scratch or have been provided by additional down-sized, sometimes company specific simulation tools – creating the well known problems.

With the scenario described in 3.1 and 3.2 this process can be supported in a very efficient way – both in terms of costs and effort. An according code export based simulation environments has been set-up by the major German car supplier Robert Bosch GmbH [5].

With the extensions described in 3.3 these models can now also be prepared for HIL simulation with again low effort and process save parameterisation.

4.2 Tilting Train Design by Co-Simulation

A project carried out at INTEC GmbH demonstrated the applicability of the co-simulation approach for a tilting train development with an industry like simulation model [Fig. 5]. Co-simulation results with Matlab Simulink have been achieved with practically identical results for the passing of a 300 m arc with 100 km/h and a track with rail imperfections compared to the simulation of the entire system directly in SIMPACK.

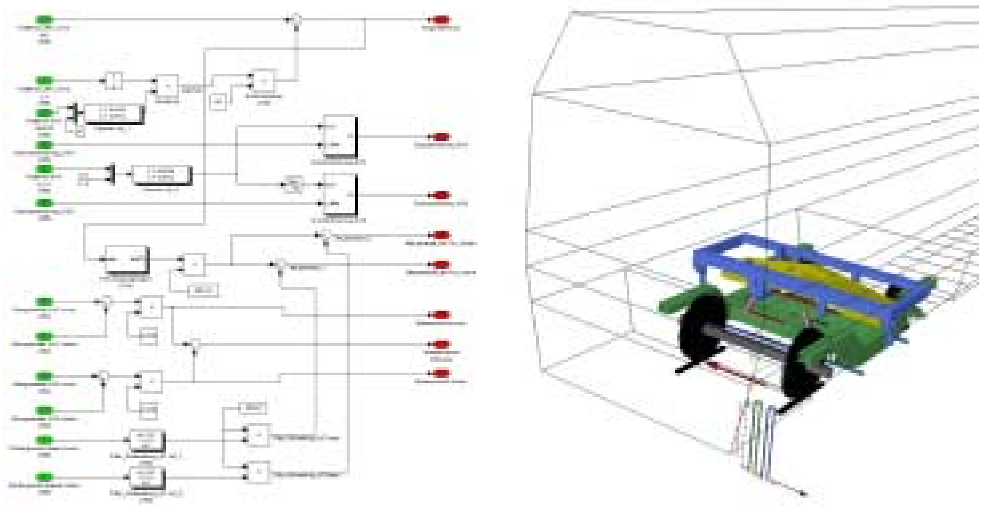

Fig. 5: Tilting Train Design by Co-Simulation between CACE (MATLAB Simulink) and MBS (SIMPACK)

4.3. An Advanced 3D Vehicle Model for Realtime Simulation

In [6] a state-of-the-art MBS car model was transferred from SIMPACK in offline set-up to DAE-free code of the equations of motion which was then running in realtime on an ETAS simulation board. For simulating a curve entry manoeuvre on a plain road the offline, DAE-based SIMPACK model took a simulation time of approximately 26 sec. for 10 sec. simulated time on a 450 Hz Pentium III CPU. By using the technology described in 3.3 the according DAE-free model ran with a realtime factor of 0,75 (simulation time / simulated time) on the same computer, i.e. the simulation took 7,5 sec. The results were identical in the frequency range of interest, no other modifications or simplifications of the model were applied.

5. Summary and Conclusions

The paper gave an overview about existing interfacing technologies between MBS and CACE with their specific advantages and disadvantages. For providing SIMPACK MBS-models for MATLAB Simulink, both for automotive and railway applications, cost efficient approaches for code export and co-simulation interfaces based on today's industry requirements have been presented together with according examples. Both methods support the know-how and data protection between companies when exchanging models.
Finally, a method to provide DAE-free models for realtime simulation of mechanical systems was introduced. This technology is the key to success when using combined mechanical and control

models for HIL simulations, for it allows to create models for HIL directly and process safely from offline models.

6. Literature

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