Virtual process chain for the optimization of operator comfort and vehicle dynamics of wheel loaders

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Abstract

This paper describes the implementation of a new automated simulation process at LIEBHERR wheel loader development focused on the global optimization of vehicle behavior. Since altering a vehicle design parameter or a configuration of an arbitrary suspension system on the machine potentially causes changes in vibration comfort, vehicle dynamic behavior, tipping safety or controllability of the machine, knowing the influence on global vehicle behavior is crucial especially in early stages of the development process.

Based on a validated full-vehicle model of a wheel loader including all relevant suspension systems and a tire model suitable for handling and comfort application, this process helps gaining insight into different behavioral patterns of the vehicle by letting it complete different driving maneuvers. The results of each maneuver are automatically processed and visualized to form detailed, maneuver-specific analyses. Outcomes from different driving maneuvers are further combined to provide the user with an overview over the vehicle behavior to be able to globally assess the effects of a certain design choice at one glance.

Kurzfassung

Dieser Beitrag beschreibt die Implementierung eines neuartigen, automatisierten Simulationsprozesses in der LIEBHERR Radlader-Entwicklung mit dem Fokus auf die globale Optimierung des Fahrzeugverhaltens. Da die Änderung eines Fahrzeugparameters oder einer Konfiguration eines beliebigen Schwingungssystems möglicherweise einen weitreichenden Einfluss auf den Schwingungskomfort, die Fahrdynamik, die Kippsicherheit oder die Kontrollierbarkeit des Fahrzeugs mit sich bringt, ist es wichtig, die Auswirkungen einer solchen Anpassung möglichst umfassend zu erkennen - insbesondere in frühen Phasen des Entwicklungsprozesses.

Basierend auf dem Gesamtfahrzeugmodell eines Radladers, welches alle relevanten Schwingungssysteme umfasst und einem Reifenmodell, welches sowohl für Handling-, als auch für Komfortuntersuchungen geeignet ist, hilft dieser Prozess dabei, Einblicke in diverse Verhaltensweisen des Fahrzeugs zu gewinnen. Hierzu werden von diesem automatisiert verschiedenste Fahrmanöver absolviert, welche jeweils spezifisch ausgewertet werden, um detaillierte und leicht interpretierbare Verhaltensanalysen zu generieren. Eine Darstellung des globalen Fahrzeugverhaltens ermöglicht es, die Auswirkungen einer Anpassung am Basisfahrzeug umfassend erkennen und bewerten zu können.

Motivation

Operator comfort today is one of the key selling points in the mobile machine industry besides efficiency, quality and productivity. While operator comfort can be described as a plurality of properties including visibility, climatic conditions, static seating comfort, noise level and others, the focus of this paper will be on the optimization of vibration comfort on mobile machines and related topics.

While travelling over rough terrain and obstacles during operation, operators of earth-moving machines are subject to vibration and shock loads. It is well known, that whole-body vibration has many short- and long-term effects on the human body ranging from accelerated muscle fatigue, reduced visual perception and fine motor capabilities to degeneration of the lumbar spine resulting in low back pain. [1][2]

By increasing the vibration comfort, productivity and safety around the worksite can be increased and at the same time the long-term effects acting on the operator are reduced. That is why continuous optimization of the vibration comfort of its vehicles is an important task at LIEBHERR wheel loader development.

State-of-the-art wheel loaders are equipped with several suspension systems including suspended seats with multiple degrees of freedom, cabin suspensions, mass damper systems to reduce travel induced oscillation and others. To be able to perform a holistic suspension optimization and investigate the influence of certain design parameters, LIEBHERR is using system simulation, which has been shown in [3].

A single change of a suspension system configuration or another design parameter might influence not only the vibration comfort behavior of the machine but also other behavioral patterns like vehicle dynamics, tipping safety or controllability. During optimization it is therefore crucial to always be aware of the global vehicle behavior especially in early stages of the development process when major concept decisions are made.

In addition, studies at LIEBHERR have shown that an increase in vibration comfort often results in operators travelling with higher speeds over a given terrain until they reach a level of vibration similar to what they were used to before. With increased travelling speeds, vehicle dynamics, tipping safety and other topics are becoming more and more relevant, which is another reason why the developer always needs to be aware of the global vehicle behavior.

Automated simulation-based optimization process

To be able to perform efficient studies on the effects of design parameters of the vehicle and to evaluate future suspension concepts and always be aware of influence on the global vehicle behavior, LIEBHERR has employed a new simulation-based optimization process.

Just like in a real testing application, specific driving maneuvers need to be performed with a virtual vehicle to investigate certain behavioral patterns in the area of vibration comfort, vehicle dynamics, tipping safety and controllability. For each driving maneuver a different set of variables and a particular way of post-processing the data is needed to get the necessary results.

Core element of the simulation process is a full-vehicle model of a wheel loader modeled in SimulationX which incorporates all relevant suspension systems. It is further connected to the structural tire model FTire via co-simulation enabling it be used in handling applications as well as driving over rough terrain and obstacles for comfort studies. The full-vehicle model has been validated with extensive measurements performed on a corresponding machine.

The simulation is remote controlled via the COM-interface by a maneuver-control-unit which has been realized in Mathworks Matlab. To define an open-loop driving maneuver, the following set of parameters is transmitted to SimulationX before each run:

- Name of the maneuver
- Definition of associated post-processing routines
- Duration of simulation run
- Relevant time interval for post-processing
- Initial position of vehicle
- Steering angle preset
- Driving velocity preset
- Loading arm initial position
- Bucket loading status
- Tire data for tires 1-4
- Ground data for tires 1-4
- Gravitational vector

For easy adjustment and overview, all driving maneuvers are globally defined in Microsoft Excel and imported to the maneuver-control-unit at the beginning of the process. New driving maneuvers can be added via Excel without the need to adjust the Matlab-code.

In addition, the user is able to define a custom parameter variation study via Excel. The related information is also imported to Matlab during initialization.

After adjusting the simulation model according to the topic of interest and starting the simulation process, the user is prompted to choose the maneuvers he wants his version of the model to perform and decides if the defined parameter study will be executed. If he chooses to, all vehicle variants are combined with all selected maneuvers in order to gain insight into the effects of the parameter variation on the global behavior of the machine.

He is presented with an estimation of the total calculation time which is calculated from the number of chosen maneuvers i and their simulation times T_i, the approximate real time factor RTF and the number of vehicle variants n.

$$T_{calc} = n \ RTF \sum_i T_i$$

Since the RTF of a full-vehicle-model in co-simulation with an advanced tire model can get well above RTF = 1 and the possible number of maneuvers and vehicle variations is only limited by the users imagination, this feature is especially useful for planning larger simulations jobs for example overnight or over the weekend.

See figure 1 for an overview of the interconnected tools utilized in the process.

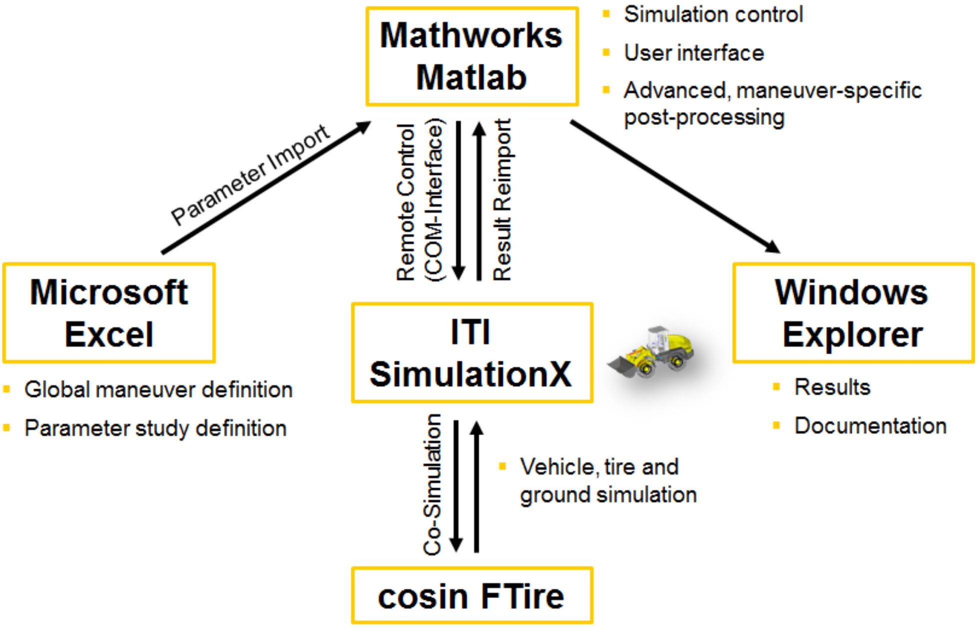

Figure 1: *Tool chain of the automated simulation process*

Post-processing and result visualization

After each simulation run a standardized set of result variables is reimported to Matlab for post-processing and result visualization. Since a lot of data can be created with this method in a short time frame, it is crucial to provide the user the information he needs in a way that allows for easy interpretation.

A two layer information approach has been realized to address this problem. The first layer provides an overview over the global behavior whereas the second layer consists of several detailed analyses specific to each driving maneuver (See figure 2).

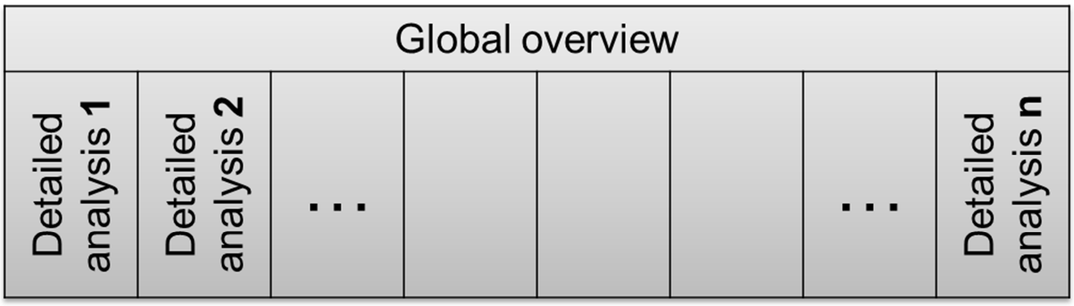

Figure 2: *Two layer information approach*

After all simulations are completed, the user is first presented with an overview of the most important results from different driving maneuvers condensed into scalar values. For visualization, a custom grouped spider plot is used and all vehicle variants can be easily compared.

Results are normalized to the values of the status-quo vehicle and processed, so that a logical improvement is always shown as a higher number, even if the corresponding value is lower than the original state. That way improvements and setbacks are easily recognized in the global behavior overview. See figure 3 for an example of the grouped spider plot.

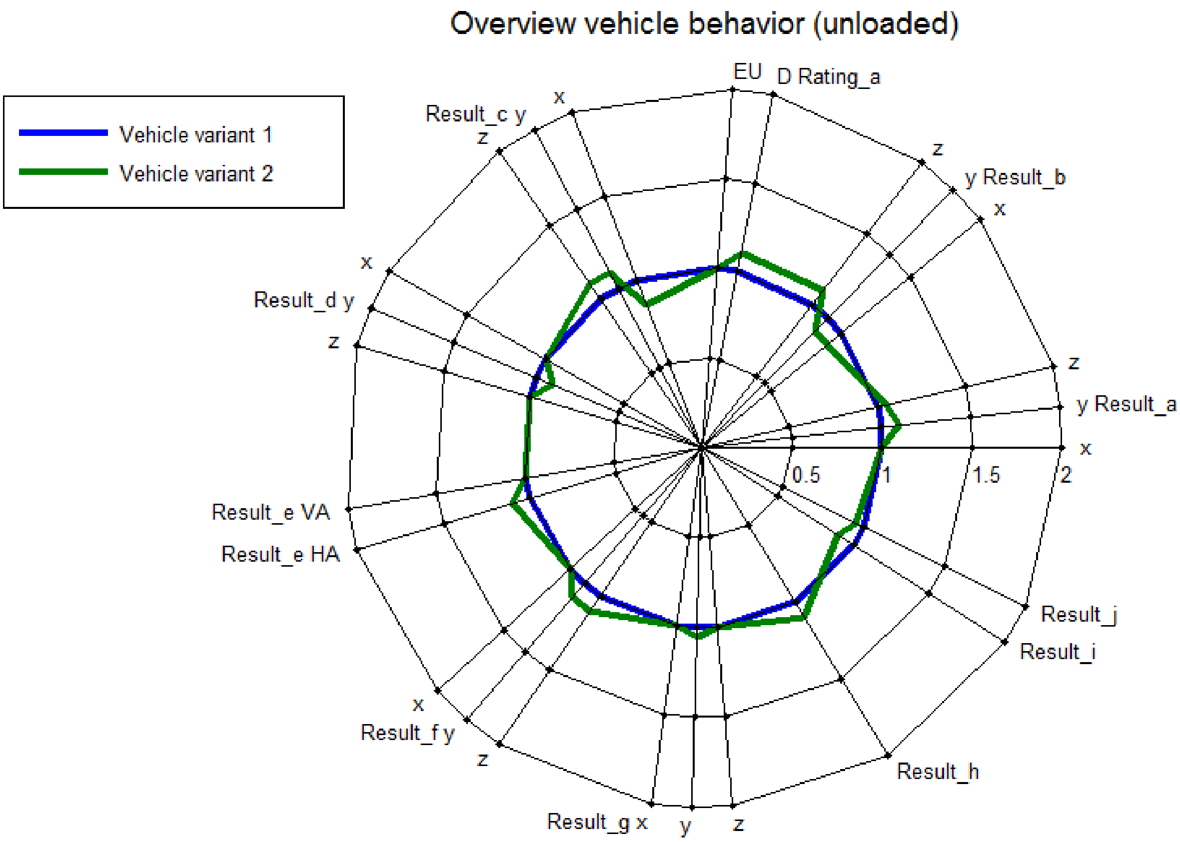

Figure 3: *Custom grouped spider plot for two different vehicle configurations*

As a next layer of information the user is provided with detailed analyses of the different driving maneuvers. As stated above, for each maneuver a different set of variables and specific ways of post-processing and visualization might be necessary to provide the user with the information he needs in a way that he can easily interpret the data.

To achieve this, a plurality of calculations and visualizations has been implemented in the post-processing-unit. Each maneuver definition contains information on the post-processing routines that will be performed after the maneuver simulation is completed.

With this modular concept it is possible to suit the needs of different maneuvers with minimum effort. While some result visualizations like a simple time series plot of the four wheel loads of the machine is needed for most of the different driving maneuvers, more specialized post-processing scripts are only related to a few maneuvers or even specific to a single one.

In addition to the driving maneuvers from which the user may choose, there is a plurality of advanced tests and calculations that are provided. While some of those are similar to typical tests on a real world vehicle like the calculation of the global center of gravity by measuring wheel loads in different vehicle orientations, others take advantage of the lack of limitations of the virtual world.

Examples include the calculation of the instantaneous centers of rotation based on several sensors positioned on a single rigid body and the usage of the intercept theorem or a systematic quantification of the static and dynamic tipping safety where the machine is forced to tip over in lots of different configurations without the drawback of real world damage.

Development of advanced suspension systems

In addition to finding the optimum compromise of configurations for today’s suspension systems to provide the best passive performance over all possible operating conditions, the presented simulation process actively supports the development of advanced suspension systems using adaptive, semi-active or active suspension technology.

An operating cycle of a wheel loader can be broken down into several cycle phases for all of which operators formulate different demands on an optimum vehicle behavior. The simulation process supports the user in developing the optimum configuration for each phase individually by representing cycle phases by different driving maneuvers and providing a specific post-processing for each one. The different optimum configurations can then be combined into a real situation-adaptive system.

Because of the system simulation capabilities of SimulationX, even semi-active or active suspension systems can be tested and evaluated according to effectiveness and efficiency. That way, the trade-off between vibration comfort, operational feedback, vehicle dynamics and tipping safety can resolved in future machine generations.

Summary

By using a modern system simulation environment like SimulationX in combination with advanced tire modeling techniques, characteristics like vibration comfort, vehicle dynamics, tipping safety and controllability can be studied on full-vehicle models in a very realistic way.

The newly designed simulation process allows efficient investigation of the effects of design parameters on the global vehicle behavior and the evaluation of future suspension concepts. Improvements and setbacks in different behavioral patterns can easily be identified by the user.

Being aware of the global behavior of the vehicle especially in early stages of the development process where major concept decisions are made helps to reduce the number of iteration loops and costly modifications in later project phases.

[1] Conway at al - A quantitative meta-analytic examination of whole-body vibration effects on human performance, Ergonomics Vol. 50, p. 228 - 245, 2007

[2] VDI 2057 - Einwirkung mechanischer Schwingungen auf den Menschen - Ganzkörperschwingungen

[3] Manuel Bös - Subsystem- and full-vehicle-simulation of mobile machines using SimulationX - 15th ITI Symposium, Dresden, 2012