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THE VIRTUAL LOAD CASE DEFINITION FOR OFF-ROAD VEHICLES: METHODOLOGY BASED ON MULTIBODY SYSTEM SIMULATION

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The methodology for setting up a multibody system for a tractor, incorporating an advanced tire model is presented and discussed. The goal is to obtain precise load and boundary conditions for the finite element analysis, which in turn aids in predicting fatigue life. Additionally, the generated loads and boundary conditions are used to define a test procedure with hydraulic actuators, aiming to replicate field damage values for the relevant components as precisely as possible. As a result, a consistent simulation process extended from the early design stage to the prototype test phase is presented in this contribution. Furthermore, all the results achieved with this methodology are confirmed by measurements.

Keywords: vehicle; multibody system; Adams; fatigue load.

1. Introduction

Defining virtual and accurate load cases is a critical challenge in modern off-road vehicle development to ensure proper dimensions and lightweight design at an early stage of development. Focusing on accurate load cases, AVL (AVL List GmbH) attempted to establish a simulation methodology comprehensively supporting the whole development process.

An agricultural tractor with a tare mass of approximately 6 tons from serial production was selected as the test object for this research (see (Jedinger-Pauschenwein *et al.*, 2024)). Unfortunately, more information about the vehicle cannot be provided because of confidentiality agreement with AVL's customer.

All simulations were conducted using simulations without considering any flexibility of the tractor body, as its rigid structure has eigenfrequencies well above the excitation spectrum of the tested road profile (<20 Hz).

Fully integrated simulation process:

– The setup of a complex multibody system model is carried out in Adams which is a multibody dynamics simulation software system (see (Adams)). The model includes an air suspended cabin with a sprung driver seat, front axle suspension incorporating the behavior of the hydraulic suspension, lashes at the rear lift hinges, elasticities in powertrain, and other details. The first parametrization of the module FTire, which is used for modelling tires (see (Gipser, 2007; FTire)), is based on approximate and scaled values.

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– Fine tuning of the tire parameters is an iterative process with multibody system simulations, whereby the parameters are adapted via measurements from the tractor testing in the field.
– Based on the fine-tuned multibody system model, traversing a field path defined by the customer is simulated with Adams. The results (accelerations, forces, etc.) are the input data (loads and boundary conditions) for the subsequent finite element analysis.
– The strength analysis with the nonlinear finite element method delivers deformations, stresses, contact behavior in the flanges, etc. A subsequent mechanical fatigue analysis provides safety factors or damage values, respectively.
– Finally, the setup of the test bed is derived from the simulation methodology and its results. It includes the arrangement of the hydraulic cylinders, the definition of the fixation of the tractor body on the test bed, and the loads and their referring cycles to achieve the same damage values at certain components as it is expected in the whole tractor lifetime.

The outstanding feature of the presented methodology is the consistent, virtual support of the development process from a design stage until prototype testing, which is not existing practice.

2. Vehicle multibody system simulation model

A vehicle multibody system (VMBS) simulation model is established (see (Popp & Schiehlen, 2010; Shabana, 2013)), including the following rigid bodies: chassis frame, rigid (pendulum) axle, cabin, and implements. The model accounts for lashes in the rear hitch, among other factors. The front axle is locked, allowing only the rotation about the longitudinal axis of the hinge as an additional degree of freedom. Springs and dampers with both linear and nonlinear characteristics are incorporated for the cabin suspension and the front/rear hitches. Various ballasting scenarios are also considered.

Tire parameters significantly impact the dynamic behavior of the entire mechanical system. To accurately account for the tires, the FTire module was utilized with initial parameter estimates provided by company cosin (see (Bayerischen Transformations- und Forschungsstiftung, 2021; FTire)) who are the software manufacturer of FTire.

For fine-tuning, acceleration measurements at the wheel hubs taken in the field (several short-wave road profiles, i.e.: cleats, see Fig. 1) have been evaluated and analyzed. The comparison with the virtually achieved simulation results formed the basis for fine adjustment of the tire parameters.

Fig. 1. Cleat obstacles for tire parametrization.

For this fine-tuning ten main parameters were varied, whereby the focus was to achieve the same acceleration signals during cleat traversing at the metering points near the wheel hubs in simulation, in the time domain as well as in the frequency domain (the Fourier spectrum) (Fig. 2).

To proof the new methodology, a merry-go-round (MGR) test track (as seen in Fig. 3) is built-up in the field. This track is specifically designed to test the durability and resilience of vehicles when exposed to real or simulated working conditions, whereby periodical excitations due to obstacles as shown in Fig. 3 are to be considered. In literature it is also referred to as a bump test track circuit with obstacles (see (Renius, 2020)).

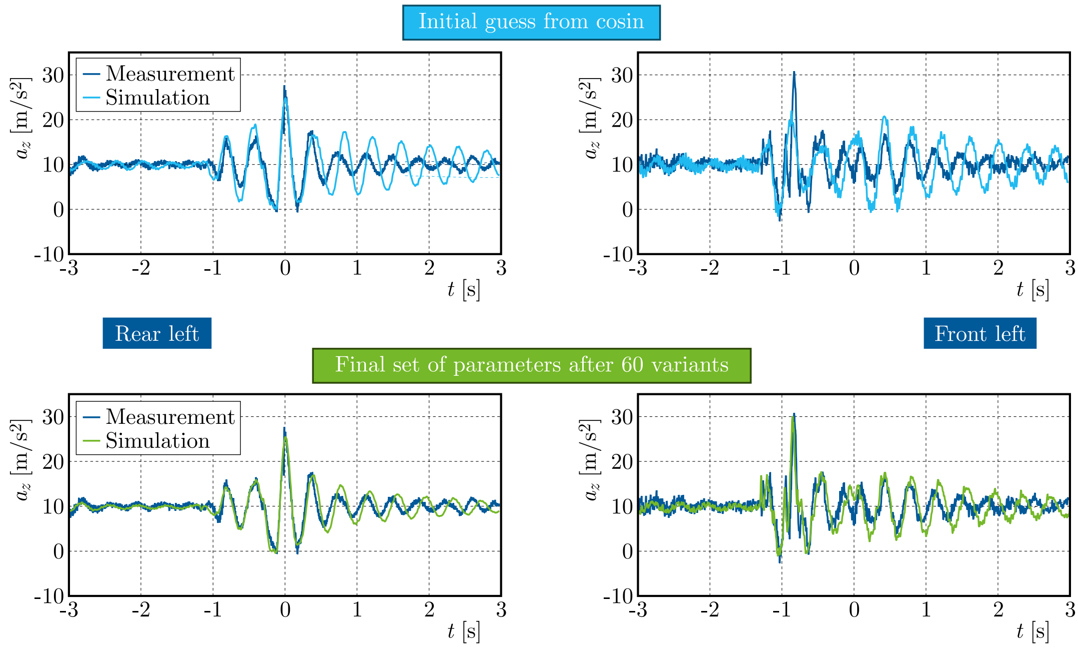

Fig. 2. Accelerations in time domain.

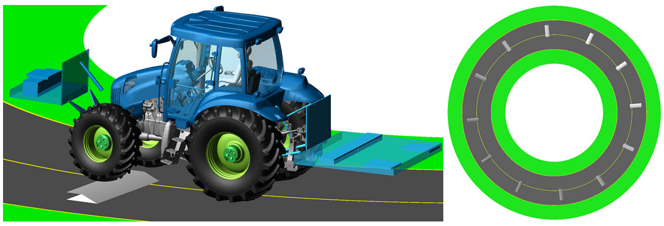

Fig. 3. Merry-go-round test.

To check the reliability of the simulation, the acceleration signals at the wheel hubs are measured again, and virtual simulations are performed with the fine-tuned model in parallel. As a result, the comparison between measured and simulated signals indicated a strong correspondence, which justifies the conclusion that a virtual multibody system simulation delivers a sufficiently accurate basis for the load case definition (see Fig. 4).

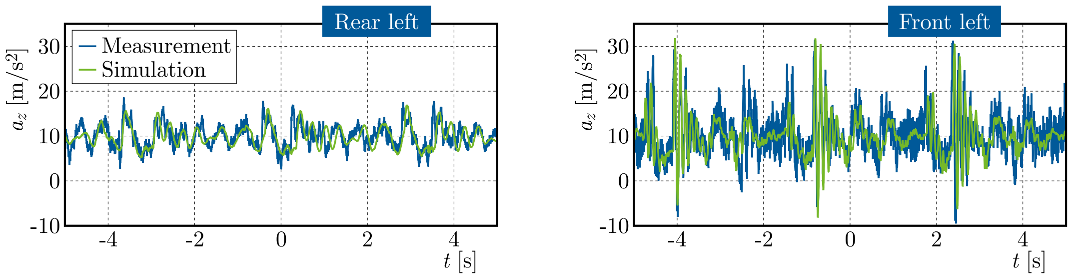

Fig. 4. Accelerations near wheel hubs in time domain during MGR test.

Additionally, these simulations enable the definition of internal forces and accelerations for all components, including those where mounting measurement sensors are impractical. Measuring intermediate/connecting forces between components directly in the field can be a quite challenging task in general, which is why the AVL “Marker Method” (Fuchs & Pauschenwein, 2019; Schiller, 2018) is a practical way to obtain them through simulation.

Because of their extent, mathematical details are not shown in the short communication paper.

3. Loads and boundary conditions

3.1. Dynamic conditions for finite element analysis

Using the validated model, loads and boundary conditions (LBC) for the finite element analysis (FEA) can now be derived from VMBS simulation results. The FEA is carried out with the software tool Abaqus (see (Abaqus)). While the straightforward approach would be to replicate the exact loading conditions from VMBS in the FE-model, this is only practical for singular events, such as accidents involving (front) wheel impacts. For durability loads under seemingly random rough road conditions, statistical methods like Rainflow counting must be applied (see (Fuchs & Pauschenwein, 2019)). However, for the periodic conditions of the MGR test track, identifying the relevant time steps within one period is more suitable.

To achieve this, the first step is to narrow down the set of all variables (forces, torques, accelerations) to a small set of relevant observables. Experience and observation have shown that the vertical forces from implements and on the axles define the critical conditions for the structural components.

This results in the desired set of forces and loads as depicted in Fig. 5.

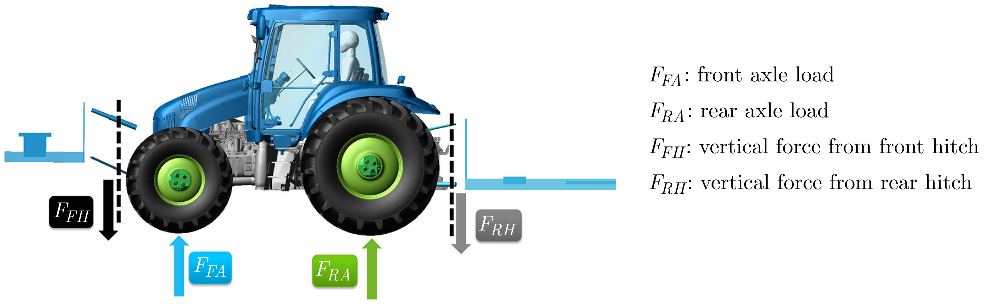

Fig. 5. Relevant observables (forces) at the chassis.

After condensing all simulated obstacle traversals into a single representative period (for all variables), the next step is to identify all local maxima and minima for the four dominant loads, combining time points that are close to each other. This selection is depicted in Fig. 6, where shock factors ($F_{\text{dynamic}}/F_{\text{static}}$) instead of forces are utilized for better visualization. Then, using the beam as an example, for each final time, the loads on the part (e.g., forces in the suspensions, rear wheel hub loads, etc.) are extracted applying the following rule: If a local extremum is nearby, the extremum is used; otherwise, the value at the specified time is used.

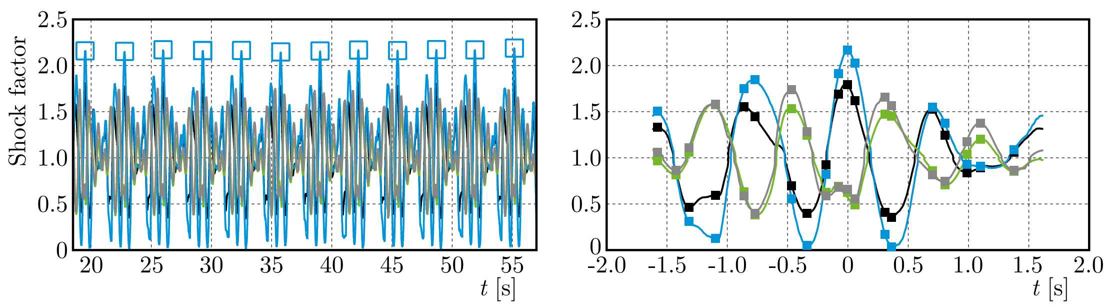

Fig. 6. Shock load factors for main forces; one full round (left), representative period (right).

All the defined load points are to be applied to the FE-model, and inertia relief warrants equilibrium of forces. Considering the constructed representative cycle, a succeeding analysis with FEMFAT/TRANS MAX obtains the damage of one period. FEMFAT is a software tool for the mechanical fatigue analysis (see (FEMFAT)). Multiplying this value with the number of cycles appearing in the whole tractor lifetime predicts the damage value.

3.2. Static conditions for hydro-pulse system and FEA

Severe load cases (e.g., pendulum impact, one-sided impact at the front wheel, etc.) require test beds with hydraulic actuators, as four-poster test beds can only apply vertical forces at the tire treads. Additionally, these test rigs with hydraulic cylinders are more cost-efficient. Therefore, a procedure has been developed to simulate the MGR test using hydraulic actuators, as shown in Fig. 7. Of course, it is not possible to determine load and boundary conditions at the test bed for the whole vehicle, but only for selected components to be investigated, because dynamic boundary conditions (i.e., accelerations) cannot be applied. Nevertheless, the hydraulic forces can be determined in a way that they are expected to cause the same damage values in the referring component as simulated in the finite element analysis described in Subsection 3.1, as the simulation results in Fig. 8 show.

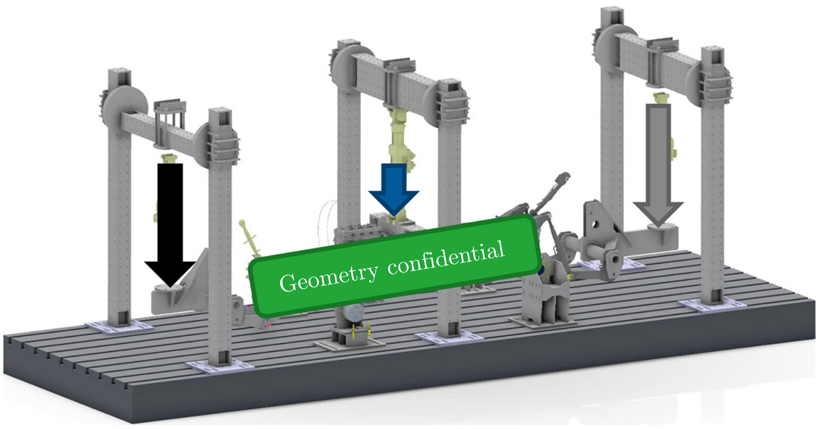

Fig. 7. Test rig with hydraulic actuators.

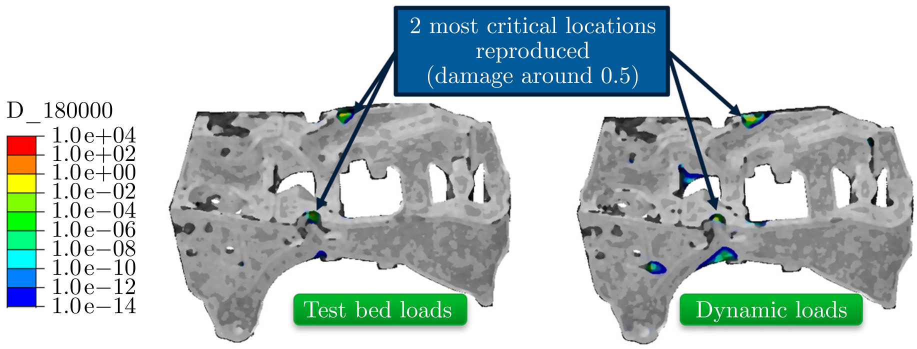

Fig. 8. Damage values test bed/dynamic loads.

4. Conclusions

A method has been developed for accurate tractor tire parametrization without a tire test-rig, which is based on measured accelerations during traversing cleat obstacles. It has been validated by a merry-go-round test track.

Moreover, a fully integrated, virtual methodology has been elaborated which supports the whole development process consistently from early design stage until prototype testing.

Although the simulation effort increases, it leads to a significant reduction in the total development costs and speeds-up the development process, as well as more accurate dimensioning of parts compared to conventional, estimated loads. It also provides valuable insight into the dynamic behavior of the tractor and allows cost-efficient optimization of parameters. Furthermore, the field conditions referring to the tractor lifetime can be precisely derived for the test bed.

Appendix. Overview of complexity levels of simulation processes

Standard simulation process (existing practice)

LBCs for FEA based on experience	Probably too severe → oversized design.
LBCs for FEA based on force measurements with similar vehicle → Lowest simulation complexity	Measurements refer to one parameter set. Parameter changes (e.g., additional mass) make LBCs unusable. In most cases test bed represents field conditions poorly.

Advanced simulation process

LBCs based on VMBS simulation, and tire parametrization is based on *approximate values* from tire database. → Elevated simulation complexity	VMBS-results deliver inferior accuracy of LBCs → mediocre accuracy of FEA-results. Inferior insight into dynamic behavior. Test bed represents field conditions with limitations.

Integrated simulation process (presented in this contribution)

LBCs based on VMBS simulation and tire parametrization with *fine-tuned values* based on measurements. → High simulation complexity	Accurate LBCs for FEA → precise FE-results. Good understanding of dynamic behavior. Test bed represents field conditions well.

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