STATE-OF-THE-ART RAILWAY VEHICLE DESIGN WITH MULTIBODY SIMULATION

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ABSTRACT

Multibody simulation is a key method for design, homologation and research of railed vehicles of all kind. Not only the classic rail-to-wheel force assessment but also many other common and advanced tasks can today be handled by MBS. This paper gives an overview of the MBS state of the art for the different fields of application, lifecycle stations and user groups in the railway industry, along with some examples of basic and advanced applications and recent research topics.

1. INTRODUCTION

The simulation of multibody dynamics (MBS), together with the finite-element simulation (FE), is one of the key methods for design, homologation and research in the field of railway and similar vehicles. The complexity of modern railway vehicles requires an as deep as possible insight into the dynamics of the vehicles already in the early stages of their development. Multibody simulation is able to avoid many costly measurements and tests as well as unexpected occurrences when the vehicle is in service. Today nearly every newly developed railed vehicle, from tramcars to high-speed trains, has undergone a thorough analysis by means of multibody dynamics.

Looking from another point of view, railway vehicle dynamics has been one of the main stimulating factors in the evolution of professional multibody simulation tools in the past. The comparatively small movements of the vehicle relative to the track allowed linear kinematics to be used in the beginning, which made the development of software tools easy. Commercial tools for railway vehicle simulation have been available already from the 1980s, alongside with a large number of "handmade" in-house tools in the industry and at universities, see, e.g., [17],[27]. Since then the number of users has drastically increased, as well as the mathematical and numerical complexity of the software, which has of course changed to fully non-linear kinematics. Now there may be several thousand licenses of commercial high-end MBS tools worldwide.

This paper tries to give a survey of today's state of the art of the multibody dynamics simulation in the railway sector. Of course not every aspect can be presented in detail and many, possibly important, points had to be left out. More information about the different topics can be found in the further reading list given at the end of the article.

2. MULTIBODY SIMULATION

2.1 What is Multibody Simulation

The aim of multibody simulation is to find in a very short time accurate answers to all questions regarding the dynamical behaviour of a mechanical or mechatronic system even if not every detail of the system is known. It is therefore predestinated for dynamical analyses and variant calculations during the whole product design and lifecycle, including the concept phase. Multibody simulation, in contrast to finite-element simulation, does not need large calculation effort; MBS software is able to run on every desktop computer or notebook, calculation times are counted in seconds, minutes or hours. See, e.g., [27],[28] or [15] for an overview of MBS and its application to vehicle systems.

Fig. 1 MBS model of a bogie with bodies ("B") and force elements ("F"), each body has 6 DOF

A multibody system is a mechanical model consisting of separate bodies that are characterised by their mass and inertia properties. They are interconnected by joints, constraints and force/torque elements. The set of joints and

constraints defines the available degrees of freedom (DOF) of the system. The movements within these degrees of freedom are influenced by the force/torque elements, which may use an arbitrary force or torque law, whether passive or actively controlled by feedback from the system. The system is completed by excitation elements and sensors for the desired measurement outputs. An example of a railway bogie is shown in Fig. 1 above.

Mathematically, the system is described by a set of – today mostly non-linear – equations of motion, i.e. differential equations of second order. Further 1st-order differential equations and algebraic equations may apply for internal states of forces and for kinematic constraints. Most MBS software packages (see Table 1 for a list) generate these equations automatically from an interactively created model of the system.

Once the equations are available they may be numerically solved in the time-domain in order to simulate the dynamical behaviour of the system and to yield time histories of positions, velocities, accelerations, forces and other important results. Another common approach is to linearise the equations in order to generate state-space matrices to which frequency-domain analysis methods can be applied. In this case the output can be, e.g., a set of eigenmodes or a root locus diagram, transfer functions or acceleration spectra.

Table 1 Some railway MBS software packages
(“c” = commercial, “r” = research, “i” = in-house)

Name	Origin	Purpose	Kinematics	Type
A’GEM	CAN	general	linear	r/c
ADAMS	US/EU	general	non-linear	c
GENSYS	S	general	non-linear	c
IFSIM	D	rail	linear	r/i
MEDYNA	D	rail	lin./nonlin.	c
MODKAT	CH	rail	lin./nonlin.	i
NUCARS	USA	rail	lin./nonlin.	r/c
ROBOTRAN	B	general	non-linear	r
SAMS	USA	general	non-linear	r
SIMPACK	D	general	non-linear	c
Univ. Mechanism	RUS	rail	non-linear	r/c
VAMPIRE	UK	rail	lin./nonlin.	c
VOCO	F	rail	non-linear	r
VOCODYM	F	rail	non-linear	r/i

2.2 Extensions

Multibody systems are not restricted to the basic principle described above. For example it is easily possible to replace the (rigid) bodies by flexible ones. These are characterised by additional degrees of freedom, covering the eigenmodes of the flexible deformations as well as additional “frequency response modes” which describe

flexible excitations caused by local deformations, see, e.g., [9],[30].

Another possible extension is to couple the (time-domain) MBS solver to another solver which cares for, e.g., automatic control loops or hydraulic, pneumatic or aerodynamic subsystems of the mechanical model. In this co-simulation approach the solvers exchange the appropriate system states at regular points in time before continuing their solution process.

2.3 State of the Art

Modern multi-purpose MBS software packages are capable of handling mechanical and multidisciplinary systems of great complexity, see, e.g. [1]. On the one hand typical MBS models of, e.g., articulated trains with fully modelled suspension and rail-to-wheel contact (see Fig. 2), or combustion engines with dynamic valve springs and fully modelled chains, have several thousand degrees of freedom, all with completely non-linear kinematics, see [14]. The frequency bandwidth covered by typical models can be as large several thousand Hertz and more. Due to their complexity these models still require calculation times far longer than the actually simulated period of time. On the other hand it is today possible to handle models with far more than 100 non-linear DOF in real-time, provided that sophisticated measures are taken to reduce the calculation effort, see, e.g., [11].

Fig. 2 MBS model of an articulated train with detailed suspension and drivetrain [32]

Numerical models of force elements are available for passive and active suspension elements of all kind, such as helical flexicoil springs, hydraulic and friction dampers, sophisticated rubber springs/dampers as well as complete airspring systems with level control. A lot of advanced friction and contact elements cover mechanical subsystems like the tooth contact between gearwheels with high accuracy and calculation speed, see, e.g., [20]. The multibody simulation of railway vehicles depends especially on the mathematical and numerical modelling

of the rail-to-wheel contact, and many different methods have been developed in the past, see, e.g., [16],[23],[31].

Modern sophisticated MBS integrators with error test, order and stepsize control and advanced Jacobian update strategy [2] are able to solve the non-linear equations of motion with high accuracy, stability and reliability. This is true even for sudden changes in the states or in the force laws, e.g. for friction and shock contact situations where fixed-stepsize integrators like an explicit or implicit Euler or a Runge-Kutta may become unstable when the chosen stepsize is not appropriate, see, e.g., [35].

Not only the actual solution of the dynamic equations but also the analysis and reporting environments of the MBS software package play a vital role in their daily use. There are powerful bidirectional data interfaces e.g. to finite-element packages, fatigue analysis tools or CAD software. The MBS solvers can be run in batch mode with automatic variation of model parameters or they can be steered by optimisation tools in order to perform automated parameter optimisation tasks, see, e.g., [13]. The simulation results can be presented not only by diagrams and result tables but also, sometimes simultaneously, by 3D animation, in order to give either a quick overview or a deeper insight into the behaviour of the vehicle, see Fig. 3.

Fig. 3 Result output page: 3D-animation with force arrows, curves with cursors moving simultaneously

3. USAGE OF MULTIBODY SIMULATION IN THE RAILWAY SECTOR

3.1 Who Uses MBS

Multibody simulation tools, whether in-house or commercial, are widely used throughout the railway sector:

Vehicle and component manufacturers use MBS simulations during the design process and after the shipment of

their products to ensure product quality and to reduce design costs – see the next section.

Operators. They use MBS either in collaboration with the manufacturers during the vehicle design process or for their own research and analyses in the field of vehicle dynamics, component design and vehicle-track dynamics. Accident prevention and analysis is another important topic for operators. In some countries there are dedicated operator- or state-related research centers, e.g. the RTRI in Japan, the KRRI in Korea, the INRETS in France or the TTCI in the United States, who all use multibody simulation as a part of their work.

Homologation authorities. They make usually no active use of MBS but require more and more not only test results but also verification results from MBS simulation in order to assess the admissibility of new vehicles.

Consultants and engineering service providers. MBS is used on a project-to-project basis according to the company's field of activity. Topics may range from component engineering over complete vehicle design up to research projects or software development.

Universities and connected research institutes. They play a vital role in keeping the research activities in the railway MBS field alive. MBS is used for teaching and research, the latter both in publicly funded projects and in collaboration with manufacturers and operators. Some institutes develop and maintain their own MBS software codes, even many commercial MBS software packages have their roots in research or university institutes. For academic teaching and most publicly funded research projects the institutes are often allowed to use the commercial tools at an extremely low price.

3.2 MBS in the Vehicle Design Process

The design process of railed vehicles differs when looking at different parts of the world, also with regard to multibody simulation. The following three examples may illustrate this:

Europe. MBS plays a vital role already in the offer phase, where feasibility studies must be carried out and several rough design concepts must be compared. For example the ordering operator company asks whether the offered vehicle would be able to cope with a difficult track situation particular to the operator's network. Once the order has arrived, the intended bogie design as well as the complete car or the whole articulated trainset each undergo thorough MBS investigations. The focus lies here on typical homologation issues like rail-to-wheel forces and stability as well as on vehicle-specific topics like drivetrain or control design, component fatigue or acoustics. Parts of the vehicle will undergo measurements in this phase (for example the bogie frame for a fatigue

verification) but typically the vehicle as a whole is only simulated and not tested until it is completely finished. The subsequent measurements are then usually already a part of the vehicle's homologation procedure. The recorded results of the homologation tests often serve as feedback for the improvement of the MBS vehicle model, in order to have a better validated model for further investigations or for possible claim management purposes.

Japan. The process is in many points similar to the European vehicle design process. However, a bogie or car will usually undergo a roller rig test before it is delivered to the customer. In Europe roller rigs are used only for special purposes like traction, drivetrain and braking analyses [19], for rail and wheel material research, or for the validation of numerical vehicle models [4].

North America. A large domain of railway vehicle development in North America is related to freight cars and powerful Diesel locomotives that are able to pull extremely long and heavy trains over large distances. Therefore especially the freight cars must above all be cheap and easy to handle and to maintain, a fact that drastically inhibits the use of complicated and highly specialised suspension or steering mechanisms. There are no dedicated high-speed railways, and passenger cars are in general not as intensively simulated as in Europe or Japan. The use of multibody simulation is therefore very limited during the design of these vehicles but it helps to assess the severe problem of rail damage from Rolling Contact Fatigue by giving insight into the loads arising from the rail-to wheel contact.

Comparison: multibody simulation in the automotive design process. The automotive industry's needs are quite different from those of the railway industry. The design process of a car is very diversified: Whilst at a railway manufacturer often the same engineer is responsible for all tasks from homologation over comfort up to acoustics, the automotive design topics are handled by different departments. Typically these are quasistatics, handling (including driver's actions and reactions and thus real-time simulation), suspension comfort, secondary comfort (influenced by engine and drivetrain vibrations etc.), NVH (noise, vibration, harshness), acoustics, durability/fatigue and finally abuse and crash.

Tests and measurements on test tracks and roller rigs are an integral part at many stages of the design process. Multibody simulation is heavily involved in all these topics, and each of these tasks may require differently specialised multibody vehicle models. High-end modelling elements, e.g. for elasto-hydrodynamic contact forces, finite-element-based large-deformation and high-frequency tyre models or complex chain and belt models have recently been developed to ensure the necessary degree of complexity and accuracy for the according models.

3.3 Simulation Versus Measurements

A test run, whether on a real track or on a test track, with purpose-made instrumented force-measuring wheelsets and sensors for movements and accelerations in the bogies and carbodies may easily take three or four weeks, not included the time for preparing the measuring equipment. The total costs for such a campaign will often be in the range of four to five hundred thousand Euro for a typical articulated commuter trainset, and accordingly higher for a high-speed train. This is multiple times the price of a complete professional commercial multibody package for railway simulations, including training and initial on-the-job familiarisation of an expert user. These numbers indicate clearly why MBS simulation plays such a vital role.

Multibody simulation can additionally assist the engineer in shortening and optimally exploiting the time required for necessary measurements and tests. For example, potential flaws of the vehicle design can already be located in early states of the engineering process. During the measurement campaign the engineer can examine these issues carefully because he knows about their existence and also their potential risks.

On the other hand each simulation model is only as reliable as its input data. The slogan "rubbish in – rubbish out" often hits the nail on the head. Probably more often than typos in the model input, unknown parameters or too much simplified force laws appear as a frequent reason for unnoticed wrong simulation results. In these cases well-directed and therefore cost-effective measurements before or during the creation of the simulation model will drastically help to increase the reliability and quality of the simulation results.

4. FIELDS OF APPLICATION

4.1 Homologation

The homologation process of railway vehicles is mainly based on measurements where a number of assessment values is compared against appropriate limit values. Of course the final authorisation of the vehicle design will indeed require an actual test run, but during the actual design process MBS is extensively used for ensuring that the vehicle will pass this test. This is done by reproducing the test scenarios, either completely or in parts, and to analyse the "measurement" outputs from the simulations. Some cases, for example a failure in airsprings or in the anti-yaw dampers at high speeds, can only be analysed by simulation.

A typical homologation process involves the items a) rail-to-wheel forces, b) derailment safety, c) stability, or critical speed, d) gauging, e) sidewind, f) crashworthiness and g) potential track damage costs due to Rolling Con-

tact Fatigue (RCF). MBS is predestinated for a), b) and c) but also the other items are often pre-analysed by multi-body simulation.

Example: Stability Analysis. The assessment of the critical speed of a railway vehicle can be done by linear or non-linear methods. The linear method is far faster but less exact, thus it is mostly used for a preliminary analysis before applying a – more exact – non-linear method, see, e.g., [24],[29]. For the linear method the vehicle model is numerically linearised, with special attention paid to properly quasilinearise the rail-to-wheel contact functions (? R function, contact angle function, roll angle function) in order to find hunting modes that correspond better to the actual profile combinations [8]. One main result is a root locus plot.

The non-linear method uses the actual vehicle model to find at which speed the wheelset hunting movement will cease after having previously been excited. A recent advanced approach to determine the critical speed more exactly is to perform a bifurcation analysis with the non-linear vehicle model, which will even reproduce the different kinds of possible limit cycles. This has been done by coupling the multibody simulation tool to path-following software, see [29].

4.2 Other Main Applications

With the increase in capabilities of the simulation tools up to the aforementioned state of the art, the number of applications has also grown over the years. Especially the simulation of passenger comfort, which requires the consideration of the carbodies' flexibility, is a common task since the operator will demand a specific comfort level to be reached. Other common and important MBS applications are: a) design and analysis of complete drivetrains with electric or Diesel motor, gearbox, couplings and flexible shafts, with the main goal of avoiding unwanted eigenmodes; b) analysis of passive and active bogie and wheelset steering mechanisms; c) optimisation of brake systems, whether pneumatic brakes, magnetic rail brakes or eddy-current brakes, with particular regard to braking distance and slide protection; d) prediction of stresses in vehicle components and, in a downstream process, the fatigue lifetime; e) assessment and optimisation of automatic control systems such as traction controllers, active suspension or tilting mechanisms, f) optimisation of the pantograph-to-catenary contact dynamics, and g) the detailed analysis of accidents, e.g. derailments, or component failure events.

Many of these tasks would actually not require the complete vehicle to be modelled. However, experience shows that there are often cross-influences between the single subsystems of a vehicle which may well be worth being considered. The modular modelling features and data interfaces of modern MBS software allow all subsystems

of a vehicle to be modelled and analysed separately and independently before they are assembled to a complete system. Moreover, the user can freely choose the degree of detail which he wants his submodels to have.

Example: Stress and Fatigue. Multibody simulation is able to generate time histories of any force or torque at any point in the vehicle. A simple way of assessing the stresses in a vehicle component is to find the maximum and minimum force that appear in the mechanical links of this component and to feed them into finite-element software in order to analyse the stress states at sensitive parts of the component. However, some critical situations may be missed due to the manual selection of the points in time to be analysed.

The complete analysis of all points in time by this method is nearly impossible due to the required calculation effort. Thus an intermediate process has been established which, if properly applied, ensures accurate stress solutions with minimal calculation time: Firstly the FE software determines an influence matrix that relates unit loads at the linkage points to the stresses in the critical (or all) areas of the structure. The resulting effort required to obtain the actual stresses from the MBS simulation results reduces then to multiplying the time-variable load vectors with the influence matrix, which can easily be done by the MBS software itself. This simple but very effective method has successfully been applied in the automotive industry [10] and could easily be used in the railway industry as well.

4.3 Advanced Topics

Many other applications of multibody simulation are currently still topics of research.

Wear and Rolling Contact Fatigue. A main point of interest is surely the simulation of the wheel and rail wear and Rolling Contact Fatigue (RCF). Whilst the scientific background of these processes is quite well-defined, the actual application to vehicle simulation models and track scenarios requires still a lot of experience and practice. One of the reasons is that the boundary conditions, such as the actual friction numbers, the rail profiles or the actual adjustment of the vehicle suspensions, are usually not well-known but must somehow be estimated. Nevertheless recent research, e.g. [12],[22], shows that reasonable results can be obtained with the aid of multibody simulation tools.

Other wear-related topics like rail corrugation or wheel polygonalisation are also topics of research in order to increase the knowledge about the different originating mechanisms and the applicability of multibody simulation to them. Among possibly others, there are two different main mechanisms where corrugation of the rails can origin from. The first one is related to excitations of

the wheelsets' torsional and lateral eigenmodes in narrow curves and results mainly from the rolling radii difference between the left-hand and the right-hand wheel. This process can well be analysed by MBS simulation in time-domain, see, e.g., [7].

The other type of corrugation appears mainly on distance and high-speed lines, i.e. on more or less tangent track, and leads to acoustic effects in the range of about 500 to 2000 Hz. It is caused by high-frequency dynamical interaction of the track superstructure with the vehicle suspension. Due to the large frequency bandwidth this phenomenon cannot easily be approached by time-domain MBS analysis yet. The common rail-to-wheel contact mechanics (Hertzian normal force, Kalker's non-linear creep force theories [16]) apply only to quite low frequencies and have to be extended for higher frequencies. Research has been done mainly in the frequency-domain sector, see, e.g., [25],[26].

Acoustics is another topic that is theoretically well-determined but difficult to handle in multibody simulation. Besides the degree of modelling detail which is required to reach large bandwidths, the need for a finite-element coupling for a complete simulation of the noise radiation make acoustics an advanced task. A recent simplified simulation approach which determines the structure-borne noise power on the surface instead of the radiated sound power could help to ease the application of MBS also in the acoustics sector, see, e.g., [6] and Fig. 4.

Fig. 4 Example of structure-borne noise power determined by MBS (from the author of [6])

Earthquakes and post-derailment. In some countries railway vehicles may experience situations that are quite uncommon in other parts of the world. Especially in Japan, which is put at risk by numerous earthquakes a year, the extensive use of high-speed trains raises an important potential danger that must be analysed by research. The pre- and post-derailment behaviour of a train during an earthquake is influenced by its suspension characteristics, the rail-to wheel contact, the track geometry and the track dynamics. All these topics can well be handled by MBS.

Besides the actual vehicle dynamics it may then be necessary to simulate not only the derailment risk but even the vehicle's behaviour after the actual derailment. Because it appears difficult to consider the behaviour and the contact mechanics of all the vehicle and track components involved in the simulation, one of the focuses lies on limiting the post-derailment destruction by additional safety elements along the track.. See, e.g., [3],[5],[21] and also Fig. 5 for an example.

Track quality analysis. The increase in train speed and exploitation of the track capacity make a regular assessment of the track and rail quality more and more difficult. Conventional methods like visual checks and the regular use of (slow) measurement vehicles are today impossible on main line tracks. Besides costly high-speed measurement trains there is a research focus on in-service track quality measurements by conventional vehicles. Both approaches require a deep insight into the dynamics of the vehicle dependent on the state and type of the track, which can only be gained by means of multibody simulation, see, e.g., [18].

Fig. 5 Derailment by earthquake in MBS simulation, track shifted laterally with 1 Hz sinus excitation

Hardware-in-the-loop (HIL) and software-in-the-loop (SIL) simulation. These methods allow components and subsystems to be tested without having built the complete vehicle, by coupling real components to simulated vehicles or vice versa. They require real-time solving of the equations of motion. Although they are not so common as in the automotive industry there are examples of usage at least on railway roller rigs, see, e.g., [19]. The very specialised in-house MBS tools for these applications may in the future be replaced by commercial tools with real-time capabilities and interfaces to real-time boards.

4.4 Special Railed Vehicles

Of course multibody simulation is not only related to the usual railed vehicles from tramways to high-speed trains. With the same generic dynamics formalism and rail-to-wheel contact elements it is also possible to simulate, e.g., roller coasters, cranes or material transport and

handling systems. (Some may object that even modern low-floor tramcars might actually not be counted to standard railed vehicles because of their complicated suspension and wheel steering system.) An example of a roller coaster MBS model is shown in Fig. 6.

Besides these vehicles there is an increasing number of so-called people movers. They usually have pneumatic tyres instead of steel wheels and guiding wheels on their sides. The vehicles are either self-driven or pulled by a rope, see, e.g., [34]. However, the principles of vehicle dynamics stay the same, and due to the long-standing application of MBS in the automotive industry there are even sufficiently exact tyre models that may be used in these vehicles.

Maglev trains have not much in common with the aforementioned vehicles but analysis topics like passenger comfort, design of suspensions, control systems or emergency guidance mechanisms will also apply to them and may be easily approached by means of multibody dynamics. The required modelling elements for a simulation of the magnetic levitation, guidance and traction/braking forces are usually not immediately parts of commercial MBS software but these force laws may easily be programmed into user-written elements or coupled to the MBS solver by co-simulation or code export from control design tools.

Fig. 6 MBS model of a roller coaster vehicle with complex track layout and wheels on three sides of the rail

5. CONCLUSIONS AND OUTLOOK

Although this paper can only provide a limited overview of the many and different fields where multibody simulation is used in research, development, design and homologation of railed vehicles of all kind, the number of given examples shows clearly the importance of this analysis method and also the wide range of its application.

However, when compared with the automotive industry, it seems that the use of multibody simulation in the railway sector is in general more limited to lower frequency ranges and uses fewer high-end modelling elements. The reasons are surely related to the fact that the railway vehicle design process is less specialised than the automotive design process and the railway industry may not be able to invest as much effort into particular comfort and handling issues as the automotive industry. But here lies also a great chance for the future of the railway multibody simulation because railway engineers may easily benefit from all new developments made available in professional multibody simulation tools.

There is a number of demanding MBS-related research topics which will help to reduce the costs for vehicle design and track maintenance and to increase the anyway high inherent safety of railway vehicles even more. It can be expected that these topics will gain importance over the following years. Current and future research, along with the continually decreasing calculation times of modern computers, will extend the widespread possibilities of multibody simulation even more.

REFERENCES

- [1] Ambrósio, J.: Multibody dynamics: a framework for multidisciplinary developments, *Proc. ACMD Tokyo* (2006).
- [2] Ascher, U. and Petzold, L.R.: Computer methods for ordinary differential equations and differential-algebraic equations, *Proc. SIAM*, Philadelphia (1998).
- [3] Boronenko, Y., Orlova, A., Iofan, A. and Galperin, S.: Effects that appear during the derailment of one wheelset in the freight wagon: simulation and testing, *Vehicle System Dynamics*, Vol. 44 Supplement, 663-668 (2006).
- [4] Bosso, N., Gugliotta, A. and Somà, A.: Numerical Simulation of a railway bogie and experimental validation using a scaled prototype on roller-rig, *Proc. ECCOMAS Multib. Dyn. Conf.*, Milan (2007).
- [5] Brabie, D. and Andersson, E.: Dynamic simulation of derailments and its consequences, *Vehicle System Dynamics*, Vol. 44 Supplement, 652-662 (2006).
- [6] Carrarini, A.: Acoustic postprocessing for multibody simulations including flexible bodies, *Proc. ECCOMAS Multib. Dyn. Conf.*, Warsaw (2009).
- [7] Collette, C., Vanhonacker, P., Bastais, R. and Levi, D.: Comparison between time and frequency studies of a corrugated curve of RER Paris network, *Wear*, Vol. 269, 1249-1258 (2008).
- [8] Cooperrider, N., Hedrick, J., Law, E. and Malstrom, C.: The application of quasilinearization techniques to the prediction of nonlinear railway vehicle re-

- sponse, *Proc. IUTAM Symp. Dyn. of Vehicles on Roads and on Tracks*, Delft, 314-325 (1975).
- [9] Dietz, S., Wallrapp, O. and Wiedemann, S.: Nodal vs. modal representation in flexible multibody system dynamics, *Proc. ECCOMAS Multib. Dyn. Conf.*, Lisbon (2003).
 - [10] Eichberger, A.: Fatigue on a Virtual Test Rig Based on Multi-body Simulation, *Proc. NAFEMS World Congress Malta* (2005).
 - [11] Eichberger, A.: Real-Time Simulation of Complex Vehicle Models, *Proc. AVEC*, Kobe (2008).
 - [12] Enblom, R.: *On Simulation of Uniform Wear and Profile Evolution in the Wheel-Rail Contact*, KTH Stockholm, Aeronautics and Vehicle Engineering (2006).
 - [13] He, Y. and Mcphee, J.: Multidisciplinary Optimization of Multibody Systems with Application to the Design of Rail Vehicles, *Multibody System Dynamics*, Vol. 14, 111-135 (2005).
 - [14] Hippmann, G., Arnold, M. and Schittenhelm, M.: Efficient Simulation of Bush and Roller Chain Drives, *Proc. ECCOMAS Multib. Dyn. Conf.*, Madrid (2005).
 - [15] Iwnicki, S. (ed.): *Handbook of Railway Vehicle Dynamics*, Taylor&Francis, Boca Raton (2006).
 - [16] Kalker, J.: *Three-Dimensional Elastic Bodies in Rolling Contact*, Springer, Wien, New York (1990).
 - [17] Kortüm, W.: Review of multibody computer codes for vehicle system dynamics, *Vehicle System Dynamics*, Vol. 22 Supplement, 3-31 (1993).
 - [18] Lubert, B., Haigermoser, A., Grabner, G., Schleinzner, G. and Hirschberg, W.: Methods for classification and track geometry evaluation based on vehicle response analysis, *Proc. VSDIA Budapest* (2008).
 - [19] Meli, E., Malvezzi, M., Papini, S., Pugi, L., Rinaldi, M. and Rindi, A.: A railway vehicle multibody model for real-time applications, *Proc. ECCOMAS Multib. Dyn. Conf.*, Milan (2007).
 - [20] Mulski, S., Mauer, L., Schlecht, B. and Rosenlöcher, Th.: Linear and non-linear analysis of drivetrains in complete systems using the 3D-multi-body simulation code SIMPACK, *Proc. ECCOMAS Multib. Dyn. Conf.*, Milan (2007).
 - [21] Nishimura, K., Terumichi, Y. and Morimura, T.: Development of Vehicle Dynamics Simulation for Safety Analyses of Rail Vehicles on Excited Tracks, *Journal of Computational and Nonlinear Dynamics*, Vol. 4, iss. 1 (2009).
 - [22] Perez, J., Stow, J. and Iwnicki, S.: Application of active steering systems for the reduction of rolling contact fatigue on rails, *Vehicle System Dynamics*, Vol. 44 Supplement, 129-138 (2006).
 - [23] Piotrowski, J. and Chollet, H.: Wheel-rail contact models for vehicle system dynamics including multi-point contact, *Vehicle System Dynamics*, Vol. 43, 455-483 (2005).
 - [24] Polách, O.: Comparability of the non-linear and linearised stability assessment during railway vehicle design, *Vehicle System Dynamics*, Vol. 44 Supplement, 129-138 (2006).
 - [25] Popp, K. and Schiehlen, W. (eds.): *System Dynamics and Long-Term Behaviour of Railway Vehicles, Track and Subgrade*, Springer, Berlin, Heidelberg (2003).
 - [26] Sato, Y., Matsumoto, A. and Knothe, K.: Review on rail corrugation studies, *Proc. International Conference on Contact Mechanics and Wear of Rail/Wheel Systems*, Tokyo (2000).
 - [27] Schiehlen, W. (ed.): *Advanced Multibody System Dynamics – Simulation and Software Tools*, Kluwer (1993).
 - [28] Schiehlen, W. (ed.): *Dynamical Analysis of Vehicle Systems*, Springer, Wien, New York (2008).
 - [29] Schupp, G.: A Software Environment for Bifurcation Analysis of Mechanical Systems, *Proc. EUROMECH 452, Advances in Sim. Tech. for Appl. Dynamics*, Halle (2004).
 - [30] Schwertassek, R. and Wallrapp, O.: *Dynamik flexibler Mehrkörpersysteme*, Vieweg, Braunschweig, Wiesbaden (1999, in German).
 - [31] Schupp, G., Weidemann, C. and Mauer, L.: Modelling the Contact Between Wheel and Rail Within Multibody System Simulation, *Vehicle System Dynamics*, Vol. 41, 349-364 (2004).
 - [32] Suarez, B., Paulin, J. and Rodriguez, P.: SIMPACK at the Railway Technology Research Centre CITEF, *SIMPACT News Feb. 2006*, INTEC GmbH Weßling (2006).
 - [33] Terumichi, Y., Suda, Y. and Sogabe, K.: Wear Development on Elastic Rail with Repeated Passages of Disks, *Proc. EUROMECH 452, Advances in Sim. Tech. for Appl. Dynamics*, Halle (2004).
 - [34] Tsunashima, H. and Sato, Y.: Dynamics of Automated People Mover Vehicle in Earthquake, *Proc. 10th Intl. Conf. on Automated People Movers, Orlando* (2005).
 - [35] Weidemann, C., Mauer, L. and Arnold, M.: Improving the calculation speed for time domain integration of complex railway vehicles, *Proc. ACMD*, Tokyo (2006).

Keynote Lecture 2

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Biography

Studied mechanical engineering at Technical University of Aachen (Germany), specialised on railway vehicle dynamics and design.

Doctorate on profile wear simulation of rubber-cushioned railway wheels.

He worked then in the research department of the German railway wheel manufacturer Bochumer Verein Verkehrstechnik GmbH, mainly on wear and polygonisation of railway wheels.

Additionally projects on process and quality management in railway workshops at BLS Lötschbergbahn, Switzerland, and Swiss Federal Railways.

Since 2001 at INTEC GmbH, Germany (multibody software package SIMPACK), several years of experience with project work for railway industry and operators in Europe and Japan.

Since 2004 account manager for railway customers and product manager of SIMPACK Rail.