ECCOMAS Thematic Conference on Multibody Dynamics 2019

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| Investigation of Tympanic Membrane Influences on Middle-Ear Impedance Measurements and Simulation |
| This study simulates acoustic impedance measurements in the human ear canal and investigates error influences due to improperly accounted evanescence in the probe’s near field, cross-section area changes, curvature of the ear canal, and pressure inhomogeneities across the tympanic membrane, which arise mainly at frequencies above 10 kHz. Evanescence results from strongly damped modes of higher order, which can only be found in the near field of the sound source and are excited due to sharp cross-sectional changes as they occur at the transition from the probe loudspeaker to the ear canal. This means that different impedances are measured depending on the probe design. The influence of evanescence cannot be eliminated completely from measurements, however, it can be reduced by a probe design with larger distance between speaker and microphone. A completely different approach to account for the influence of evanescence is to evaluate impedance measurements with the help of a finite element model, which takes the precise arrangement of microphone and speaker in the measurement into account. The latter is shown in this study exemplary on impedance measurements at a tube terminated with a steel plate. Furthermore, the influences of shape changes of the tympanic membrane and ear canal curvature on impedance are investigated. |
| Anterior Cruciate Ligament Injuries Alter the Kinematics and Kinetics of Knees with or Without Meniscal Deficiency |
| The purpose of this paper was to study the biomechanical behaviors of knees with anterior cruciate ligament deficient (ACLD) with or without a combined medial or/and lateral meniscal injury during level walking. The motion capture system and the modeling system (AnyBody) were applied to simulate the kinematic and kinetic properties of knees. The results show that the knees with ACLD exhibited significantly less extension than the control knees at the mid stance. A lower extension moment and adduction moment in all ACLD-affected knees were detected during the terminal stance when compared with control knees. The ACLDML group showed significantly lower proximodistal compressive forces and anteroposterior and mediolateral shear forces, while the shear forces tended to increase in the ACLD, ACLDL, and ACLDM groups. |
| Investigation of Inhomogeneous Stiffness and Damping Characteristics of the Human Stapedial Annular Ligament |
| This study describes a non-contact measuring and system identification procedure for evaluating inhomogeneous stiffness and damping characteristics of the annular ligament in the physiological amplitude and frequency range without the application of large static external forces that can cause unnatural displacements of the stapes. To verify the procedure, measurements were first conducted on a steel beam. Then, measurements on an individual human cadaveric temporal bone sample were performed. The estimated results support the inhomogeneous stiffness and damping distribution of the annular ligament and are in a good agreement with the multiphoton microscopy results which show that the posterior-inferior corner of the stapes footplate is the stiffest region of the annular ligament. |
| Comparison of Measured EMG Data with Simulated Muscle Actuations of a Biomechanical Human Arm Model in an Optimal Control Framework – Direct Vs. Muscle Synergy Actuation |
| We developed a biomechanical digital human model (DHM) simulation framework that uses (synergetic) Hill type muscles as actuators and optimal control (OC) for motion generation. In this work, we start investigating the underlying actuation signals of the Hill type muscles. We have set up a *weight lifting test* (‘biceps curls’) in the motion lab, where we measure the muscle activation via electromyography (EMG). The via muscles actuated simulation model produces human like trajectories for different types of OC cost functions, whereas the underlying muscle actuations strongly differ from each other. Our first results indicate that a muscle synergy actuation is more robust concerning the variation of activation signals and that a specific mix of cost functions preserves the resulting motion behavior while producing more human like actuation signals. |
| A Detailed Kinematic Multibody Model of the Shoulder Complex After Total Shoulder Replacement |
| Multibody modeling allows reproducible and comparative analyses of shoulder dynamics after total shoulder replacement (TSR). For inverse dynamics an accurate representation of the musculoskeletal kinematics from motion capture is fundamental. Although current optimization-based approaches effectively identify the underlying skeletal motion in terms of position, velocities and accelerations are not consistently provided. The purpose was therefore to introduce a multibody model of the shoulder complex after TSR implantation with detailed representation of the muscle apparatus that directly generates the musculoskeletal kinematics from motion capture data. The inherent inverse kinematics problem is resolved by implementation of a potential field method. Sensitivity analysis was performed to determine the model’s tracking capability. Scapular motion showed overall good agreement with measurements from the literature. The approach yields equivalent results to current approaches with the benefit of directly computing accelerations without formulation of an optimization problem. The multibody model presented will be used for further inverse dynamics analyses regarding various loading conditions of different TSR designs. |
| Multibody Analysis of a 3D Human Model with Trunk Exoskeleton for Industrial Applications |
| This paper presents a multibody analysis of a 3D human model with a wearable exoskeleton for trunk support in industrial applications. Multibody computational models reveal to be a suitable solution for investigating the human-exoskeleton interaction, for properly developing the mechanical design and for analyzing the effect on human joints loads. With the final aim of developing a proper wearable device for the support of human trunk during manual lifting tasks, a 3D multibody model of human body interacting with an exoskeleton has been implemented. Different position of exoskeleton assistance joints and two assistance levels are investigated in terms of human waist and hip joints loads reduction and interface forces at contact points. The results comparison allows defining maps of most suitable and critical areas for exoskeleton joints positioning. |
| A Hill Muscle Actuated Arm Model with Dynamic Muscle Paths |
| This contribution presents the optimal control of a musculoskeletal multibody model with Hill muscle actuation and dynamic muscle paths. In particular, the motion of a human arm and its muscle paths is described via constrained variational dynamics. The optimal control problem in this work is based on the direct transcription method DMOCC [[4](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_7#ref-CR4)], where the optimal control problem is discretised in time, and the resulting nonlinear constrained finite dimensional optimisation problem is solved. To take a step towards finding global or multiple minima, we utilize the MATLAB multistart framework for global optimisation. With the help of an example, we outline a framework to find feasible solutions and analyse several minima to which the nonlinear programming solver converges. |
| Optimal Control Simulations of Two-Finger Precision Grasps |
| Grasping is a complex human activity performed with readiness through a complicated mechanical system as an end effector, i.e. the human hand. Here, we apply a direct transcription method of discrete mechanics and optimal control with constraints (DMOCC) to reproduce human-level grasping of an object with a three-dimensional model of the hand, actuated through joint control torques. The equations of motions describing the hand dynamics are derived from a discrete variational principle based on a discrete action functional, which gives the time integrator structure-preserving properties. The grasping action is achieved through a series of constraints, which generate a hybrid dynamical system with a given switching sequence and unknown switching times. To determine a favourable trajectory for grasping action, we solve an optimal control problem (ocp) with an objective involving either the contact polygon centroid or the control torques subject to discrete Euler-Lagrange equations, boundary conditions and path constraints. |
| Reinforcement Learning Applied to a Human Arm Model |
| In this contribution, we focus on a muscle actuated human arm model [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_9#ref-CR1)] and discuss the applicability of Reinforcement Learning (RL) [[2](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_9#ref-CR2)] in order to control it. The content is divided into five sections. We start with the introduction of the human arm model and continue with the optimization method the authors of the model applied. Afterwards, we bring the optimization problem into a form such that RL can handle it and introduce the RL approach we are planning to apply. Before we close with the conclusion, we have a look at the results of the techniques in the numerics section. |
| Dynamic Modeling and Analysis of Pool Balls Interaction |
| This work presents the development, test and verification of a pool billiard model in the context of Multibody System Dynamics (MSD) methodologies. This study aims at examining and comparing the effects of considering several different contact forces models when dealing with impact and frictional phenomena. Thus, during the contact events two kinds of forces are considered, i.e., normal contact forces and frictional forces. |
| Dynamics of Machine-Process Combinations |
| Machines and mechanisms realize processes, from the shaping process of a milling machine to the motion process of an automotive system. The dynamics of a machine generated by a properly chosen set of constraints in combination with an appropriate drive system is designed to meet the prescribed requirements of some process, which is done by projecting the machine equations of motion on the process dynamics and thus by looking at the process as a system of additional constraints. The presentation presents a corresponding approach applying multibody system theory in combination with transformations from the machine side to the process side and vice versa. Practical aspects are discussed and an example given. |
| Modeling of Elastic Cages in the Rolling Bearing Multi-Body Tool CABA3D |
| The paper is concerned with the dynamical simulation of rolling bearings with elastic cages in the simulation software CABA3D (Computer Aided Bearing Analyzer 3D). The modeling process (import of finite element models, model reduction, model verification) is considered in detail. Two different contact simulation methods (slice contact and node-to-surface contact approaches) are shown and compared. |
| Analysis of the Influence of the Links’ Flexibility and Clearance Effects on the Dynamics of the RUSP Linkage |
| A mathematical model of the RUSP linkage with a flexible link and clearance in a revolute joint is presented. In the proposed model it is assumed that the clearance exists only in the cut-joint. A new spatial model of the revolute joint with a radial and axial clearance is proposed. In this approach, the clearance joint is discretized by means of the contact elements located on the cylindrical and frontal surfaces of the journal and bearing which can automatically detect collisions between contacting bodies. The normal contact force is modelled using the Nikravesh-Lankarani formula. The LuGre friction model is applied to model tangent friction force. Flexible link is discretized by means of the Rigid Finite Element method. In simulations, the influence of the link’s flexibility and clearance in the revolute joint on the dynamic response of the linkage is analyzed. |
| Multibody Analysis and Design of an Electromechanical System Simulating Hyperelastic Membranes |
| This work presents the multibody analysis and design of an electromechanical system (named robotics membrane) able to replicate the non-linear behavior of hyperelastic membranes. The designed robotics membrane is able to change its stiffness reproducing the deformation of different kinds of membrane. An actuator is controlled to adapt the length of the flexible elements, inside the robotics membrane, in order to modify the stiffness of the whole system. An analytical and numerical modelization in SimMechanics™ have been developed. The model validation has permitted to simulate the robotic membrane deformation in different load conditions in order to compare the results with the behavior of real hyperelastic membranes. The obtained results validated our system and underlined that our idea is concrete and applicable in the real environment. |
| Haptic Simulation of Mechanisms |
| Mechanisms with non-uniform transmission ratios are used by humans in everyday and industrial environments. Often, these transfer or guidance mechanisms are hand-actuated. Approaches to develop ergonomic products with high perceived quality, such as Human-Centered Design, require prototypes. In order to provide prototypes of mechanisms to be designed regularly and at an early development stage, haptic feedback systems can be used to simulate virtual prototypes and make them haptically perceptible by the user. This contribution discusses challenges of this *haptic simulation* and introduces measures to increase overall performance. This includes an integration scheme, a passivity controller implementation, a beneficial friction model and *haptic simulation* of direct dynamics. Furthermore, adaptation of mechanisms during *haptic simulation* is presented in order to allow fast and convenient evaluation of virtual prototypes. |
| Solution Techniques for Problems of Inverse Dynamics of Flexible Underactuated Systems |
| A new approach to the inverse dynamics of flexible mechanical systems is proposed. In contrast to the commonly applied sequential discretization in space and time, a simultaneous space-time discretization of the problem at hand is proposed. In particular, two alternative approaches are investigated: (i) a space-time finite element formulation, and (ii) the method of characteristics. The focus is put on mechanical systems whose motion is governed by quasilinear hyperbolic partial differential equations. Numerical examples are presented which confirm that the two alternative methods under investigation can be successfully applied to the considered class of underactuated mechanical systems. |
| Investigation of the Behavior of Vibration-Damped Flexible Link Robots in End-Effector Contact: Simulation and Experiment |
| Lightweight robots with flexible links are perfect candidates for applications which require contact with the environment due to their inherited compliance. However, due to the lower stiffness compared to typical industrial robots it is imperative to handle occurring link vibrations. This can be done with different vibration damping control approaches. This paper focuses on a method based on analytical estimation of the joint torques using accelerometers. The joint torques are estimated by reconstruction of the link dynamics. This is valid as long as no external forces are present. Stability of a robot with active vibration damping control in a contact scenario is essential. In this regard the switching caused by unilateral contact must be investigated carefully. In this paper the stability of the control system is verified in simulation and moreover in an experiment. |
| Possibilistic Investigation of Mechanical Control Systems Under Uncertainty |
| Uncertainty in linear control systems is often modeled by real- or complex-valued perturbations. The key idea of robust control techniques is to check whether the design specifications are satisfied even for the worst-case uncertainty. A quite intuitive and apparently natural way to model uncertainty is using fuzzy sets and arithmetic. The resulting uncertain system models do not only consider worst-case scenarios, but also the shape of uncertainty modeled by imprecise quantities. Possibilistic measures can then be employed to investigate the satisfaction of stability and performance objectives and to draw conclusions about the robustness of the resulting controller. The gradualness in the quantification of uncertainty allows for more comprehensive statements than just worst-case scenarios. |
| Nonlinear Position Control of a Very Flexible Parallel Robot Manipulator |
| In this paper, we investigate the control of a very flexible parallel robot with high accuracy. This robot has two very flexible long links and can be modeled as an underactuated multibody system since it has fewer control inputs than degrees of freedom for rigid body motion and deformation. Therefore, these flexibilities are taken into account in the control design. In order to obtain high performance in the end-effector trajectory tracking, an accurate and efficient nonlinear controller is designed. This nonlinear feedback controller is based on the Lyapunov approach using the measurable states of the system. Then, it is carefully tested on the flexible parallel robot. The simulation and experimental results show that the end-effector tracks desired trajectories with high accuracy. Also, the designed controller is compared to previous works and the results show that the controller can achieve higher tracking performance. |
| A Compliant and Redundantly Actuated 2-DOF 3RRR PKM: Best of Both Worlds? |
| Due to their deterministic behaviour, compliant mechanisms are well-suited for high-precision applications. In this paper the benefits of redundant links and actuation are investigated in terms of increasing support stiffness and homogenising actuator loads.  The manipulator is modelled with lumped inertia properties of the links and non-linear relations for the joint stiffnesses. The lumped parameter model allows a fast system level performance optimisation of the joint geometry simultaneously exploiting joint pre-bending and preloading, where the stiffness matrices of all joints are computed numerically efficient with non-linear flexible beam elements.  This model is applied to optimise the design of a compliant and redundantly actuated 2-DOF 3RRR parallel kinematic manipulator. The improvement of support stiffness is demonstrated with an analysis of the first parasitic natural frequency. Balancing of the actuator torques is concluded from a potential energy analysis. |
| On the Modeling of Redundantly-Actuated Mechanical Systems |
| Dynamics modeling is essential in the design and control of mechanical systems, the focus of the paper being *redundantly-actuated systems,* which bring about special challenges. The authors resort to the *natural orthogonal complement* (NOC) to derive the dynamics model; benefiting from the elimination of the constraint wrenches, the NOC offers a simple and systematic alternative to the modeling of the systems of interest, which leads to low computational demands. The actuator torques/forces are found by means of a minimum-norm solution; then, by relying on the QR-decomposition, a simple, robust procedure is applied to compute the optimum solution, while obviating the explicit computation of the right Moore-Penrose generalized inverse, which requires the inverse of a product that is prone to ill-conditioning. The methodology is illustrated with an application to a redundantly-actuated parallel-kinematics machine with three degrees of freedom and four actuators. |
| An Individual Pitch Control Concept for Wind Turbines Based on Inertial Measurement Units |
| Wind turbines are mainly designed by their fatigue behaviour. These fatigue behaviour can be mainly influenced by the control algorithm. So wind turbine designer struggle to enhance their control strategies to minimise the fatigue loads acting on their wind turbines. In this contribution an advanced control strategy for individual pitch control is presented, where no sensors within the blades are necessary. The loads in the blades are reconstructed by simplified models representing the characteristic dynamics of the wind turbine. The models are supported by a single Inertial Measurement Unit (IMU) within the nacelle measuring the translational accelerations and angular velocities about the three independent axis. This contribution mainly focus on the development of the concept, while practical tests will be a future task. Nevertheless, the single steps of the reconstruction and control concept are validated using a well established multibody model. |
| Localized Helix Configurations of Discrete Cosserat Rods |
| Cosserat rods [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR1)] are the prefered choice for modeling large spatial deformations of slender flexible structures at small local strains. Discrete Cosserat rod models [[6](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR6), [7](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR7)] based on geometric finite differences preserve essential properties of the continuum theory. In previous work [[9](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR9)] kinetic aspects of discrete quaternionic Cosserat rods defined on a staggered grid were investigated. In particular it was shown that equilibrium configurations obtained by energy minimization correspond to solutions of finite difference type discrete balance equations for the sectional forces and moments in conservation form. The present contribution complements the numerical studies shown in [[9](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR9)] by considering localized helix configurations [[2](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_23#ref-CR2)] of discrete Cosserat rods as more complex benchmark examples. |
| Importance of Warping in Beams with Narrow Rectangular Cross-Sections: An Analytical, Numerical and Experimental Flexible Cross-Hinge Case Study |
| This paper reports on the significance of warping deformation on the stability analysis of a flexible cross-hinge mechanism, which consists of two leaf springs with rectangular cross-section. The effect of misalignments in this mechanism is studied analytically, numerically and experimentally. An analytical buckling analysis is carried out to determine the theoretical critical load of a generalized cross-hinge mechanism on the basis of first principles. A geometrically nonlinear beam finite element with a non-uniform torsion description is used to model the leaf springs numerically. The change in natural mode frequencies and stiffness as a function of the misalignment is determined by a multibody program. Measurements from a dedicated experimental set-up confirm that the inclusion of warping effects is crucial, even for narrow rectangular cross-sections: it is found that the effects of warping increase the analytical critical buckling load of the system by 55%. |
| Robust and Fast Simulation of Flexible Flat Cables |
| In this work we will present a novel approach to compute the potential energy and its derivatives of a shell discretized by finite elements. Afterwards a special solution strategy for quasistatic equilibrium problems with moving boundary conditions is presented. At the end numerical examples are shown, which demonstrate the benefits of this methods in simulating flexible flat cables. |
| Dynamic Analysis of Compliant Mechanisms Using Absolute Nodal Coordinate Formulation and Geometrically Exact Beam Theory |
| Compliant mechanism mainly relies on large deformations of compliant rods to transmit motions, forces and energy. The geometric nonlinearity of the compliant rods is one of the most serious challenges when accurate modeling and dynamic simulation are performed. The absolute nodal coordinate formulation (ANCF) and geometrically exact beam theory (GEBT) are employed to investigate the nonlinear modeling and analysis of compliant mechanisms in this paper. By taking account of deformation characteristics of the compliant rod at the external connection, a new ANCF beam element with one nodal deformation constraint is proposed. Based on the locking alleviation technique, strain split method, the effect of the locking phenomenon of the ANCF beam element on the dynamic simulation of compliant mechanism is investigated. In comparison, the Euler-Bernoulli beam element, which is a kind of locking free GEBT element, is also used for the dynamic analysis of the compliant mechanism. Finally, the numerical example of a partial compliant four-bar mechanism is presented to illustrate the accuracy and effectiveness of ANCF and GEBT beam elements for the dynamic problems of compliant mechanisms. |
| Dynamic Performance of Flexible Composite Structures with Dielectric Elastomer Actuators via Absolute Nodal Coordinate Formulation |
| The composite structure with the dielectric elastomer (DE) and soft materials is the main form in the actuators in soft robots. The accurate dynamic model for this composite structure is important for the design and the manipulating control of soft robots. In this paper, the high-order shell elements are developed to descript the mechanical performance of composite two-layer plate based on the absolute nodal coordinate formulation (ANCF). The constitutive model for DE material and Mooney-Rivlin constitutive model for soft material are introduced. The consistent condition of deformation for composite structure is proposed when the two-layer composite shells are united together. The effects of various parameters such as voltages and material parameters on the dynamic performance of composite structure are studied. The results show that the oscillation amplitude and frequency of the free end of the composite structure increase nonlinearly with the increase of the excitation voltage. The increase of structural stiffness for the DE plate may improve the periodicity and stability of the deformation. The results may provide guidance for the dynamic modelling and actuation design for soft robots. |
| Approaches to Fibre Modelling in the Model of an Experimental Laboratory Mechanical System |
| In this paper there are presented some possible approaches suitable for the modelling of the fibre and cable dynamics in the framework of various mechanical systems: force representation of a fibre, a point-mass model and an absolute nodal coordinate formulation. Experimental measurements focused on the investigation of the fibre behaviour were performed on an assembled weight-fibre-pulley-drive laboratory mechanical system. This mechanical system was modeled using all of the mentioned methods (newly using point-mass model) and simulations of the experimental measurements were performed. Results obtained using simulations and experimental measurements are compared and discussed. |
| Body-Fluid-Structure Interaction Simulation for a Trailing-Edge Flexible Stabilizer |
| In this paper there are presented some possible approaches suitable for the modelling of the fibre and cable dynamics in the framework of various mechanical systems: force representation of a fibre, a point-mass model and an absolute nodal coordinate formulation. Experimental measurements focused on the investigation of the fibre behaviour were performed on an assembled weight-fibre-pulley-drive laboratory mechanical system. This mechanical system was modeled using all of the mentioned methods (newly using point-mass model) and simulations of the experimental measurements were performed. Results obtained using simulations and experimental measurements are compared and discussed. |
| Investigation of a Model Update Technique for Flexible Multibody Simulation |
| In modern engineering applications, the build up of representative numerical models may be not feasible or involves considerable effort. As a result, the need for experimental investigation on the real structures and the implementation of the measured results into the numerical model arises. Within this contribution, the integration of experimentally derived data into the model build up process of a flexible body within multibody dynamics is investigated. In contrast to the conventional modelling approach, the experimental based approach omits the need of an underlying finite element model of the flexible structure. Both approaches are investigated and compared on a simple experimental test case of a flexible beam-like structure. |
| Extension of the Iterative Improved Reduced System Technique to Flexible Mechanisms |
| In the present work the iterative Improved Reduced System technique (IRS) is extended to flexible mechanisms to include the joint constraints. Starting from the two-step method described in [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_31#ref-CR1)] by the same authors, we create an iterative method similar to the iterative IRS used in structural mechanics. Finally, the method is applied to a RSCR spatial mechanism to find the natural frequencies. |
| Updating of Finite Element Models for Controlled Multibody Flexible Systems Through Modal Analysis |
| Model updating is widely used for the estimation of the correct parameters of finite element models. Indeed, model accuracy should be as high as possible to synthesize controllers and observers, as well as for fault detection. Model updating based on experimental measurements is hence necessary to ensure model correctness.  A procedure tailored for updating dynamic models of flexible-link multibody systems (FLMSs) modelled through ordinary differential equations is proposed in this paper. The aim is to correct mass, stiffness matrices for modeling accurately the main vibrational modes in the frequency range of interest. Once consistency between the model coordinates and the modal data is obtained through a suitable transformation, model updating will be solved an optimization problem that also accounts for bounds on the feasible values. The method exploits model linearization, since it allows for modal analysis.  The paper also discusses some issues in performing experimental analysis in the presence of FLMSs that are not in an asymptotically stable equilibrium configuration. First of all, it is proposed, and also validated experimentally, the use of balancing springs. Then, it is discussed theoretically and numerically the use of active control to set the mechanism in an asymptotically stable equilibrium configuration, by tackling the issues of spillover due to the controller. |
| Modelling Rigid and Flexible Bodies with Truss Elements |
| The truss element, due to its simplicity, can fulfill the need to model multibody systems in a way that reduces the size of the problems or improves the efficiency of calculations. The truss element can be used to model rigid and flexible bodies as well as several joints with a single truss element or with aggregates built up from a number of truss elements. With an extended mass description, planar binary rigid links or links that can undergo a uniform dilatation with pin joints can be modelled by a single truss element. Planar ternary elements can likewise be modelled by three truss elements. In three dimensions, a rigid body can be modelled by six truss elements along the edges of a tetrahedron, but also three truss elements can be combined to form a triangular membrane element or six truss elements to form a constant-strain finite solid element. Applications to two benchmark problems and a Delta robot are given. |
| State Observation in Beam-Like Structures Under Unknown Excitation |
| Measuring and logging of fatigue loads is essential for individual life time estimations of dynamically loaded mechanical structures like operating wind turbines. A fundamental intermediate step is the accurate derivation of structural displacement fields at all critical spots, for which, in practical applications usually only a limited number of sensor information is available. Another challenge is the generally unknown system excitation, e.g. by wind loads. This contribution investigates fundamental requirements for the implementation of Unknown Input Observers (UIO) on flexible mechanical systems. To also account for large nonlinear motions, we propose a substructuring approach, which is demonstrated and validated by two numerical examples: (1) A finite element model of a comparatively simple cantilever beam structure, (2) A detailed flexible multibody model of a small-scale wind turbine test stand. |
| Dynamic Modelling of Lower Mobility Parallel Manipulators |
| This paper deals with the dynamic modelling of lower mobility parallel manipulators using the screw theory. The proposed approach is developed by considering both the permitted and restricted virtual displacements of a parallel manipulator, leading to the evaluation of intensities of the wrenches of actuations and constraints applied on the moving platform. By introducing the complementary part in terms of generalized constraint forces/torques, it completes the dynamic model of lower mobility parallel manipulators, and provides a feasible way to investigate the dynamic interactions between the limbs and the moving platform. |
| Mathematical Model of a Crane with Taking into Account Friction Phenomena in Actuators |
| A mathematical model of a crane with a tree structure of a kinematic chain and with closed-loop sub-chains is presented in the paper. The formulated model takes into account the flexibility of supports, link, rope and drives. Dry friction in joints is also considered. It is assumed that the clearances in joints are neglected. The formalism of joint coordinates and homogeneous transformation matrices, based on the Denavit–Hartenberg notation, are used to describe the kinematics of the crane. The equations of motion are derived using the Lagrange equations of the second kind. These equations are supplemented by the Lagrange multipliers and constraint equations formulated for each cut-joint. The flexible link is modelled using the Rigid Finite Element Method. |
| Closed Form of the Baker-Campbell-Hausdorff Formula for the Lie Algebra of Rigid Body Displacements |
| This paper demonstrates the existence of the closed form of the Baker-Campbell-Hausdorff (BCH) formula for the Lie algebra of rigid body displacement. For this, the structure of the Lie group of the rigid body displacements SE3SE3 and the properties of its algebra Lie https://media.springernature.com/lw20/springer-static/image/chp%3A10.1007%2F978-3-030-23132-3_37/MediaObjects/486143_1_En_37_Figa_HTML.png are used. Also, using the isomorphism between the Lie group SE3SE3 and the Lie group of the orthogonal dual tensors, a solution of this problem in dual algebra is given. |
| Alternative Integration Schemes for Constrained Mechanical Systems |
| Various methods for solving systems of differential-algebraic equations (DAE), e.g. constrained mechanical systems, are known from literature. Here, an alternative approach is suggested, which is called collocated constraints approach (CCA). The idea of the method is inspired by a co-simulation technique recently published in [[11](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_38#ref-CR11)] and is based on the usage of intermediate time points. The approach is very general and can basically be applied for arbitrary DAE systems. In the paper at hand, implementations of this approach are presented for Newmark-type integration schemes [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_38#ref-CR1), [9](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_38#ref-CR9), [12](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_38#ref-CR12)]. We discuss index-2 formulations with one intermediate time point and index-1 implementations based on two intermediate time points. A direct application of the approach for Newmark-type integrators yields a system of discretized equations with larger dimensions. Roughly speaking, the system increases by factor 2 for the index-2 and by factor 3 in case of the index-1 formulation. It is, however, straightforward to reduce the size of the discretized DAE system by using simple interpolation techniques. Numerical examples will demonstrate the straightforward application of the approach. |
| Implementation of Linear Springs and Dampers in a Newmark Second Order Direct Integration Method for 2D Multibody Dynamics |
| This paper presents the mathematical developments required to introduce both linear springs and dampers into the second order Newmark method for the integration of Multibody System Dynamics (MBSD) for bidimensional problems. The advantage of the Newmark approach is that it integrates directly the second order differential equations found in MBSD, thus not duplicating variables and reducing computational cost [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_39#ref-CR1)]. The use of Newmark approach for MBSD is not new, but it is solved usually in a quasi-Newton procedure [[2](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_39#ref-CR2)], which is easier to implement, but has worse convergence than a full Newton approach. For the full Newton approach to be achieved, however, all derivatives have to be computed analytically. In a previous work [[3](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_39#ref-CR3)], the analytical derivatives needed for simple mechanisms including Bodies, Revolute and Prismatic joints were presented. The novelty presented in this document is the development of the derivatives needed for the introduction of linear springs and dampers. The resultant Karush-Kuhn-Tucker system is solved by means of the null space method ([[4](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_39#ref-CR4), [5](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_39#ref-CR5)]). The method has been developed and tested using Newton-Euler formalism and Cartesian coordinates to solve several 2D problems. Some examples are included, which have been contrasted with ADAMS. This is a preliminary work in order to afterwards develop the method for three dimensional problems. |
| On the Numerical Treatment of Nonlinear Flexible Multibody Systems with the Use of Quasi-Newton Methods |
| This paper deals with the use of quasi-Newton methods for dynamical simulations of nonlinear flexible multibody systems which are modelled using absolute nodal coordinate formulation (ANCF). Three ANCF beam elements are briefly reminded and implemented. The Newmark integration method for index 3 differential-algebraic equations is coupled with the iterative quasi-Newton method in order to reduce computational time. The described algorithm is implemented and tested on the benchmark problem of a flexible pendulum. |
| Interior-Point Solver for Non-smooth Multi-Body Dynamics with Finite Elements |
| The increasing complexity of dynamic simulations involving unilateral constraints, such as contacts, is pushing for new solvers that may address the problem of handling non-smooth impact events in a more efficient and accurate manner, especially in mixed rigid and flexible-bodies simulations. For this purpose, a new implementation of an interior-point solver for Quadratic Cone Programming is proposed. Even though the general idea of considering multibody system formulations as a parallel of an optimization/programming problem is already known in literature ([[3](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_41#ref-CR3), [4](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_41#ref-CR4), [6](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_41#ref-CR6)]), still very few options are available for those problems whose complexity is due to contacts with friction *and* finite-elements at the same time. The opportunity to handle those problems in a unified numerical framework could trigger a novel interest both in scientific and applied researches. |
| A Fast Explicit Integrator for Numerical Simulation of Multibody System Dynamics |
| A computationally efficient explicit integrator is proposed to solve the differential-algebraic equations (DAEs) in multibody system dynamics. Algebraic constraint equations in the DAEs are regularized by a simple stabilization method, yielding a set of first order ordinary differential equations (ODEs), whose large eigenvalues are located at the negative real axis. Those ODEs have specific stiff characters, and are integrated by a class of explicit integrators (the Runge-Kutta-Chebyshev family of ODE integrators) with large stability zones on the negative real axis, so as to achieve large step-sizes at the same requirement of accuracy. The integrator adopted in this work is of fourth order, verified by practical example, and compared to several popular integrators. The high efficiency of the explicit integrator renders it a good option for practical simulations of the dynamics of constraint mechanical systems. |
| The Discrete Hamiltonian-Based Adjoint Method for Some Optimization Problems in Multibody Dynamics |
| A computationally efficient explicit integrator is proposed to solve the differential-algebraic equations (DAEs) in multibody system dynamics. Algebraic constraint equations in the DAEs are regularized by a simple stabilization method, yielding a set of first order ordinary differential equations (ODEs), whose large eigenvalues are located at the negative real axis. Those ODEs have specific stiff characters, and are integrated by a class of explicit integrators (the Runge-Kutta-Chebyshev family of ODE integrators) with large stability zones on the negative real axis, so as to achieve large step-sizes at the same requirement of accuracy. The integrator adopted in this work is of fourth order, verified by practical example, and compared to several popular integrators. The high efficiency of the explicit integrator renders it a good option for practical simulations of the dynamics of constraint mechanical systems. |
| Dynamic Parameters Optimization and Identification of a Parallel Robot |
| A common issue of the parallel robot is that has a large number of dynamic parameters, which requires a lot of processing time, whether in dynamic modeling, identification or control. The optimization and estimation of inertial parameters of a large DoF number of robotic system is crucial to tune the model-based control law in order to improve the robot accuracy. In this paper, we present an optimized number of dynamic parameters, called base inertial parameters. As a result, only 90 base inertial parameters affect the evr@ simulator instead of 210 standard one. Torque signals evaluation from experimental parallel platform and the developed analytical form show the effectiveness of the obtained results. |
| Partial Shaking Force Balancing of 3-RRR Parallel Manipulators by Optimal Acceleration Control of the Total Center of Mass |
| This paper deals with the problem of shaking forces balancing of 3-RRR planar parallel manipulators. It is known that this problem can be solved by optimal mass redistributions of the moving links, i.e. by adding counterweights or auxiliary structures. In this paper, the reduction of shaking forces of 3-RRR planar parallel manipulators is accomplished by the optimal trajectory planning of the common center of mass of the manipulator, which is carried out by “bang-bang” profile. Such a method allows a considerable reduction in shaking forces without adding any counterweight. Using such a solution, the disadvantages of adding counterweights have been avoided. An increase in the mass of moving links usually leads to an increase in shaking moments and input torques. It has been shown via numerical simulations that the use of the “bang-bang” profile is a more efficient not only for shaking forces minimization but also for minimization of shaking moments and input torques. The efficiency of the suggested balancing approach is illustrated by numerical simulations carried out via ADAMS software. |
| Energy Expenditure Minimization for a Delta-2 Robot Through a Mixed Approach |
| Energy efficiency is an important goal of robotic design, especially within the framework of Industry 4.0. In this paper, a methodology is proposed to reduce the energy consumption and is then demonstrated on a two-degree-of-freedom parallel robot (i.e. a Delta-2 robot) performing cyclic pick-and-place operations of a predefined trajectory. We define a *mixed approach* as a methodology that exploits two kinds of energy reducing systems: springs for storing elastic energy and capacitors for recovering braking energy. Using an optimization-based design methodology, two torsional springs with optimum stiffness values are coupled with energy-recuperating drive axles, leading to a reduction of motor torque required. Results show that this approach allows for a significant reduction in energy expenditure. |
| Training a Four Legged Robot via Deep Reinforcement Learning and Multibody Simulation |
| In this paper we use the *Proximal Policy Optimization* (PPO) deep reinforcement learning algorithm to train a Neural Network to control a four-legged robot in simulation. Reinforcement learning in general can learn complex behavior policies from simple state-reward tuples datasets and PPO in particular has proved its effectiveness in solving complex tasks with continuous states and actions. Moreover, since it is model-free, it is general and can adapt to changes in the environment or in the robot itself.  The virtual environment used to train the agent was modeled using our physics engine *Project Chrono*. Chrono can handle non smooth dynamics simulation allowing us to introduce stiff leg-ground contacts and using its Python interface *Pychrono* it can be interfaced with the Machine Leaning framework *TensorFlow* with ease. We trained the Neural Network until it learned to control the motor torques, then various policy Neural Network input state choices have been compared. |
| Two General Index-3 Semi-Recursive Formulations for the Dynamics of Multibody Systems |
| A couple of decades ago, the dynamic simulation of complex multibody systems in real-time was an objective difficult to achieve. Nowadays other type of problems, more demanding in terms of computational time, need to be solved like, e.g., the design optimization or the optimal control of multibody systems requiring the fastest dynamics formulations available. MBSLIM (Multibody Systems at Laboratorio de Ingenieria Mecanica) multibody library includes some global formulations for the dynamics of multibody systems. The extension of the library to accommodate topological formulations in relative (joint) coordinates is in progress and the implementation of two of them is described in this work. With this extension in the scope, some topological formulations derived in the past are revisited, generalized and reformulated. The need for generalization of the previously published formulations, was detected because the equations proposed were not general enough to be integrated in an all-purpose multibody library in natural coordinates like MBSLIM, especially because both set of coordinates need to coexist, the definition of the mechanisms has to be the original one and the library has to be automatic and all the existing models have to work with the new approach. Moreover the new solver takes advantage of some problems solved in natural coordinates, like the initial position and velocity problems for closed-loop systems. Finally to test the new equations two benchmark problems are presented: a spatial slider-crank mechanism and the chain and anchor system of a ship. |
| Real-Time Capable Calculation of Reaction Forces of Multibody Systems Using Optimized Bushings on the Example of a Vehicle Wheel Suspension |
| This paper presents an object-oriented modeling method capable of simulating the dynamics including the reaction forces of multibody systems with kinematic loops in hard real-time, called RTOOM. The modeling method describes the system by explicit equations, which can be solved numerically stable with a standard explicit numerical integrator with fixed step size. By knowing the application and the desired accuracy, the model can be adapted to fit the problem. Algebraic loops are resolved with low-pass filters parameterized for the frequency range of the application. Bushings with optimized spring and damping constants are used to avoid iterative methods for solving kinematics loops. For the optimization, a high accurate, non-manipulated and non-real-time multibody model is used. The optimization targets are stability, computing time and accuracy. The double wishbone suspension of the Formula Student racing car A40-02 of the University of Duisburg-Essen is used as an example. It has been successfully proven that a simulation up to 30 Hz with a required step size of 1 ms can be achieved. The simulation results show a very good accuracy up to 15 Hz with a deviation of the force below 4% and the acceleration below 7%. If the parameterization of the bushings remains the same, the accuracy is still acceptable even at higher frequencies. |
| A Machine Learning Approach for Minimal Coordinate Multibody Simulation |
| Over the years, a wide range of generalized coordinates have been proposed to describe the motion of rigid and flexible multibody systems. Depending on the type of formulation, a different equation structure is obtained for the model. Most formulations rely on a redundant number of Degrees Of Freedom (DOFs) and some associated constraints, leading to a set of Differential-Algebraic Equations (DAEs) to model the system dynamics. On the other hand, the ‘Minimal Coordinate’ formulation describes the dynamics through a minimal amount of DOFs and leads to a system of Ordinary Differential Equations (ODEs). For many applications, this ODE structure is an important benefit, as it enables a natural integration for state-estimation and model-based control. The backside of this approach is that it is generally not-straightforward to find a minimal number of parameters to unequivocally describe the system configurations, especially for complex mechanisms. In this work, a machine learning approach based on Auto-Encoders is proposed to find a non-linear transformation that leads to a minimal parameterization of the motion. It is shown that such non-linear transformation can be used to project into minimal coordinates while its inverse permits to perform the simulation in the reduced dimension and re-obtain the original coordinates. |
| Efficient Particle Simulation Using a Two-Phase DEM-Lookup Approach |
| We present a fast, data-based approach to predict soil-tool forces. In an expensive offline phase, we perform time-consuming particle simulations based on the Discrete Element Method (DEM). Relevant tool parameters, more specifically cutting depth, angle of incidence and velocity in longitudinal direction are varied to obtain a significant data range of the tool forces and moments. The data is stored in a structure, which we call a Lookup Table (LUT). In an online phase, we use the tool parameters to access the Lookup Table data and to obtain a meaningful approximation of the soil-tool interaction forces. |
| DARTS - Multibody Modeling, Simulation and Analysis Software |
| This paper describes the *Dynamics Algorithms for Real-Time Simulation (DARTS)* software for multibody dynamics modeling, analysis and simulation. DARTS is in use for closed-loop simulation for aerospace, ground vehicle, robotics applications and large, multi-scale molecular dynamics applications. DARTS is designed for high-fidelity multibody dynamics, fast computational speed, to handle run-time configuration changes, and to provide a broad family of computational algorithms for analysis and model based control. This paper describes DARTS capabilities, novel aspects of its architecture and design, and application examples. |
| Optimization of Geometric Parameters and Stiffness of MultiUniversal-Joint Drive Shaft Considering the Dynamics of Driveline |
| The design of multi-universal-joint drive shaft is essential for alleviating vehicle vibration. This paper proposes a novel and practical optimization method to reduce the vibration caused by multi-universal-joint drive shaft. Specifically, a dynamic model of a powertrain system including engine, shafts and universal joints is built in MATLAB which is an inalienable part of the fitness function when optimizing. Further, based on the model above, Genetic Algorithm (G.A.) is applied to optimize the drive shaft’s parameters: spatial positions and phase angles of universal joints and thickness of shafts’ shells. In each iteration of the G.A., the model is simulated under critical condition which is found by a field test of an experimental vehicle. What’s more, to verify the effectiveness of the optimization method, results from G.A. is adopted in a full-vehicle model built in ADAMS, indicating that the peak of torsional vibration is reduced greatly. |
| Application of Multibody Dynamics in the Modelling of a Limited-Slip Differential |
| The paper is aimed at suitable approaches to the modelling and dynamical analysis of a special class of automotive differentials called limited-slip differentials. The design and function of the differential are briefly introduced and suitable multibody approaches to its modelling are proposed and discussed. The modelling formalism is based on Cartesian coordinates, while rigid bodies and their mutual interaction characterized by contact and friction forces and torques should be considered. Chosen numerical results documenting the effects of various differential model parameters are shown. |
| Lateral Dynamics of Vehicles on a “Steerable” Roller Test Stand |
| Semi-autonomous and autonomous driving vehicles will pose new challenges for functional tests in the End of Line area, requiring novel roller test stands. In comparison to conventional vehicles, a higher amount of functionalities has to be validated. Furthermore, functional tests will be performed driverless. Therefore, a novel roller test stand with steerable roller sets has been developed that allows to control the position of the vehicle in the test stand fully automatically, even if there is a steering angle. The concept of the roller test stand is shown. The lateral dynamics of a vehicle on the “steerable” roller test stand is analyzed by means of a simple multibody model. The design of the control structure via virtual commissioning is illustrated. A concept for the application for functional tests is presented. |
| Dynamic Interaction of Heavy Duty Vehicles and Expansion Joints |
| The “Smart Bridge (Intelligente Brücke)” project cluster, initiated by the German Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) and the Federal Ministry of Transport and Digital Infrastructure (BMVI), focuses on “smart” monitoring devices that allow an efficient and economic maintenance management of bridge infrastructures. Among the participating projects, the one presented herein focuses on the development of a smart expansion joint, to assess the traffic parameters on site. This is achieved by measuring velocity and weight of crossing vehicles. In reference measurements, performed with a three-axle truck and a typical tractor semi-trailer combination with five axles in total, it was shown that the interaction between the vehicle and the expansion joint is highly dynamic and depends on several factors. To get more insight into this dynamic problem, a virtual test rig was set up. Although nearly all vehicle parameters had to be estimated, the simulation results conform very well with the measurements and are robust to vehicle parameter variations. In addition, they indicate a significant influence of the expansion joint dynamic to the peak values of the measured wheel loads, in particular on higher driving velocities. By compensating the relevant dynamic effects in the measurements, a “smart” data processing algorithm makes it possible to determine the actual vehicle weights in random traffic with reliability and appropriate accuracy. |
| A Study on the Behaviour of the Rotating Disk with the Damage on the Tread |
| As the evaluation method for the extent of the damage of the wheel tread of a railway vehicle, the measurement of its length in the rotational direction has been adopted for the decision of the wheel treatment. It is derived from the assumption that the depth of a wheel flat, which is one of the most serious damages, is proportion to its length in the rotational direction. Although the length of a shallow scrape tends to be long, the profile of the wheel with the long shallow scrape has less amount of irregularities compared with an exact circle. Therefore, in order to clarify the effect of the rotating wheelset with the shallow scrape on a bogie, we focused on the behaviour of the rotating wheel with the shallow scrape and evaluated it by dynamic model simulation and bench tests for an actual bogie. By the numerical simulation, we comprehended that the shallow scrape causes the vertical acceleration of the axlebox and the impact force to increase linearly in accordance with the running speed-up, and the vertical acceleration has a local maximum value around 110 km/h in accordance with a decrease in vertical collision velocity of the wheel with the roller in a higher speed range. |
| Multibody Dynamics Analysis of Railway Vehicle with Independently Rotating Wheels Using Negative Tread Conicity |
| In order to improve running stability and curving ability of railway vehicle with independently rotating wheels, an innovative structure, independently rotating wheels with negative tread conicity was proposed by one of the authors of this paper. Since the proposal of this structure, dynamics analysis based on simplified model had been implemented by means of simulation and scale model experiment. But precise numerical analysis has not been handled under the framework of multibody dynamics analysis to date. To this end, the multibody dynamics analysis of railway vehicle with independently rotating wheels using negative tread conicity is carried out in this paper. The modeling process is presented in detail, and for dealing with wheel/rail contact problem in railway vehicle, the velocity transformation and differential algebraic equation combination method is exploited. The simulation results indicate that the dynamics performance associate with running stability and curving ability could be improved by virtue of using negative tread conicity wheels. |
| A Full-Vehicle Motion Simulator for Railways Applications |
| The present study attempts to develop a 3D multi-body dynamic model of a train. First, a software is developed to simulate the longitudinal dynamics of the train by treating the train body as a point mass moving on a track. It has applications in railway operations like runtime estimation, trajectory calculation, and route planning. Additionally, a 3D dynamic model of the train was built to gain insights into the motion of train components in response to forces arising from wheel-rail interaction and external track inputs. Finally, a method is proposed to realistically capture the motion of an N-compartment train as it traverses along the entire journey, for a typical route used by the trains in India. |
| Simulation of the Maglev Train Transrapid Traveling on a Flexible Guideway Using the Multibody Systems Approach |
| In this paper, an elastic multibody model is presented describing the vertical dynamics of the maglev train Transrapid. The vehicle is represented by a rigid multibody system with five bodies and ten degrees of freedom, whereas the guideway is modeled as an Euler-Bernoulli beam. The coupling of vehicle and guideway is realized by discretized magnet forces. The control laws for the magnet forces which are responsible for keeping the air gap between vehicle and guideway at a nearly constant value are approximated by PID-T1 control laws. The model is used for simulations of the vehicle crossing the guideway with velocities up to 600 km/h. Based on these simulations, system dynamics like guideway deflections and vehicle accelerations are analyzed. |
| Omni-Vehicle Dynamical Models Mutual Matching for Different Roller–Floor Contact Models |
| Our goal is to build up an efficient computer model of the omni-vehicle comprising several omni-wheels (each one carries several freely rotating rollers on its periphery); the vehicle rolls without control on a horizontal plane. For simulating contact interaction we use the holonomic non-ideal constraints instead of ideal non-holonomic ones. Although there exist papers on the dynamical models of the vehicle and its control, e. g. [[1](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_61#ref-CR1), [2](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_61#ref-CR2)], here we study how the algorithm for computing the contact forces between a particular roller and the plane influences a description of the vehicle dynamics. To simulate dynamics we build up our dynamical models using Modelica language of object-oriented modeling. Earlier we proposed the contact tracking algorithms [[3](https://link.springer.com/chapter/10.1007/978-3-030-23132-3_61#ref-CR3)] for the point-contact dry friction regularized by linear saturation function. Using numerical simulations of the models developed we compare the vehicle dynamics for three particular contact models: (a) ideal non-holonomic contact “with impacts”, (b) model of viscous friction with the large coefficient of viscosity, and (c) one with the regularized dry friction concentrating mostly on the tangent forces description. |
| Adjustment of Non-Holonomic Constraints by Absolutely Inelastic Tangent Impact in the Dynamics of an Omni-Vehicle |
| We consider the motion of a vehicle with omni-wheels that moves along a horizontal plane without slipping. The mass of the rollers is non-zero and influences the dynamics of the system. The system is a multibody system of rigid bodies with non-holonomic constraints. The angular speed of the roller that enters in contact with the plane does not obligatorily satisfy the conditions of non-slipping. We propose to consider the vanishing of this slippage as a tangent inelastic impact. We get the analytic formula for the velocities after impact. It allows simulating the motion as a piecewise smooth system with switches. |
| Multibody Models and Simulations to Assess the Stability of Counterbalance Forklift Trucks |
| Assessing the stability of counterbalance forklift trucks is a problem of primary interest, since critical safety issues related to their operation are involved. Indeed, forklifts are the most common vehicles for material handling in industry. The stability limit is typically verified through experimental tests, which are costly and time consuming. This study aims at developing numerical tools to reliably predict the stability limit through simulations. Such tools should permit, on one hand, to partially reduce the amount of experimental tests necessarily required and, on the other hand, to support the design phase of new products since the early stages. A multibody model taking into account the compliance of the tires and of the mast assembly is developed. An experimental campaign to validate the model is ongoing. The preliminary numerical results confirm the model as a promising tool to estimate the stability limit of the forklift with satisfactory accuracy. |
| Automatic Differentiation in Multibody Helicopter Simulation |
| In a first approximation, helicopters can be modeled by open-loop multibody systems (MBS). For this type of MBS the joints’ degrees of freedom provide a globally valid set of minimal states. We derive the equations of motion in these minimal coordinates and observe that one has to compute Jacobian matrices of the bodies’ kinematics with respect to the minimal states. Classically, these Jacobians are derived analytically from a complicated composition of coordinate transformations. In this paper, we will present an alternative approach, where the arising Jacobians are computed by automatic differentiation (AD). This makes the implementation of a simulation code for open-loop MBS more efficient, less error-prone, and easier to extend. To emphasize the applicability of our approach, we provide simulation results for rigid MBS helicopter models. |