

An Applied Approach for Large-Scale Multibody Dynamics Simulation and Machine-Terrain Interaction

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ABSTRACT

Virtual Product Development (VPD) is a key enabler in CAE and depends upon accurate implementation of multibody dynamics. This paper discusses the formulation and implementation of a large-scale multibody dynamics simulation code. In the presented formulation, the joint variables are used as the generalized coordinates and spatial algebra is used to formulate the system equations of motion. Although the presented formulation utilizes the joint variables as the generalized coordinates, closed-loop mechanisms can be easily modeled using impeded constraints. Baumgart stabilization approach is used to eliminate the constraint violations without using the expensive Newton-Raphson iterations. Integrated rigid and flexible body dynamic simulation allows accurate prediction of structural loads, stress, and strains. Both modal and nodal flexible body approaches are discussed in the paper. In the presented formulation, the vehicle-terrain interaction can be easily modeled and integrated in the multibody code.

INTRODUCTION

In the last three decades, computer simulation of machine dynamics had become an integral part of VPD. Machine design, test, and performance analysis engineers have long recognized the importance of developing accurate numerical models for VPD. The development of mathematical models depicting wheeled vehicles has received considerable attention. Compared to this effort, fewer studies have been directed to models for tracked vehicles. Two essential differences exist between the models for these two classes of vehicles: the representation of the traction elements and the number of bodies in the tracked vehicle. Another difficulty in modeling the tracked vehicle is to capture the high frequency impacts between the track links and the supporting and driving parts such as: sprockets, road wheels, rollers, and idlers. General-purpose commercial multibody simulation packages are available and have the capability to handle large number of bodies. However, modeling the tracked vehicle with the high frequency dynamics leads to very long simulation time.

Although several models have been developed for the tires [9], few models for the tracks have been developed. In some simulation scenarios, the track dynamics was ignored or the soil-track interaction was modeled using a simple compliant element which can be attributed to the complexity of track-soil physics. However, in order to make VPD a seamless process, it should be able to predict/simulate the tracked vehicle performance during different operations, different work cycles, and working in different environments. This requires full 3D machine models that can handle all machine dynamics and at the same time efficiently and accurately include the effect of the track soil-interaction.



Figure 1 Full detailed model of Track Type Tractor

This paper briefly describes the formulation and implementation of a general-purpose in-house multibody dynamics simulation code, TomSim. With the requirements and deficiencies described above, TomSim was developed, designed, and optimized to model large-scale multibody systems. Specialized kinematic and force modules were developed to model the physics of the different machine components, interaction between the machine elements, and interaction with the soil. In order to accurately model the machine loads, TomSim is interfaced with another in-house discrete element program that is used to model aggregate systems (Rocks3D™). Figure 1 shows the different components of a Track Type Tractor and the level of details that can

be handled by TomSim. Figure 2 shows a snapshot of typical co-simulation between TomSim and Rocks3D™. The shown scenario depicts dynamic simulation of a typical loading-dumping work cycle of tracked hydraulic excavator loading a wheeled off-highway truck. In this simulation the actual external dynamic loads were calculated from Rocks3D™ and applied to the corresponding bodies in the respective machine.

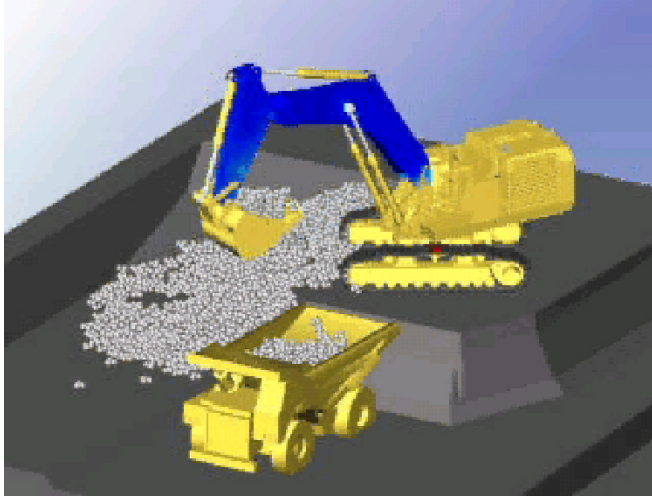


Figure 2 Hydraulic excavator loading off-highway truck

TomSim utilizes a recursive scheme to evaluate the equations of motion without numerical difficulties that may arise from the change in the track configuration. Singular configurations can be avoided by continuously changing the structure of the recursive equations. The sensitivity of the predictor-corrector multistep numerical integration schemes to the method of formulating the state equations is demonstrated.

This paper is organized as follows. In the following section the structure of the equation of motion of the multibody system is introduced. The open loop and closed-loop kinematic models are introduced and the equation of motion is discussed. Including the flexible body dynamics into the equations of motion is presented. In Section 3, the constraint treatment in the multibody system is discussed. Section 4 provides a brief outline of the recursive algorithm implemented in TomSim. In Section 5, discusses the static equilibrium analysis of the multibody system. In Section 6, the tire model and track-soil interaction are presented. Section 7 presents some examples of the simulation results that can be performed using this general-purpose software. Finally, some conclusions are drawn.

EQUATION OF MOTION OF MULTIBODY SYSTEM

TomSim's equation of motion is formulated based on the velocity transformation technique (joint-based formulation). Historically, the joint based formulation didn't allow closed loop kinematics. Since most machine systems contain closed-loop mechanism, as shown in

Figure 3, developing a multibody code without closed loop capability will limit the scope of applications of this code. Many researchers have demonstrated that the joint-based formulation can be extended to model closed loop system. In TomSim, the closed loop kinematic models can be modeled using impeded constraints.

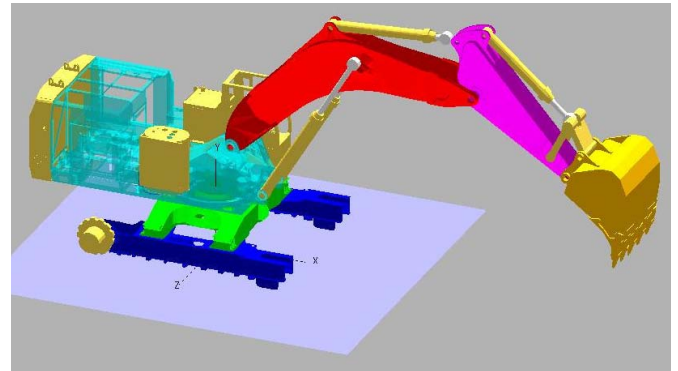


Figure 3 Partial model of tracked excavator.

EQUATION OF MOTION OF UNCONSTRAINED SYSTEM

The equation of motion of the multibody system can be derived using many different approaches. One of the most famous approaches is the Lagrangian form which can be written as follows:

$$M^{qq} \ddot{q} = Q \quad (1)$$

This form of the equation of motion lead to the minimum set of differential equations that are function of the system generalized coordinates. The joint reaction forces can be calculated using a set of Lagrange multipliers. Also, the equation of motion can be written in the Newton-Euler form as follows:

$$\begin{bmatrix} M^{cc} & J^{cT} \\ J^c & 0 \end{bmatrix} \begin{bmatrix} a^c \\ -\lambda \end{bmatrix} = \begin{bmatrix} g^c \\ \gamma \end{bmatrix} \quad (2)$$

Newton-Euler form has the advantage of expressing the equation of motion in terms of the Cartesian coordinates which simplifies the expressions for the constraints and the forces. TomSim takes the advantage of both methods to express the equation of motion.

TomSim equations of motion for rigid multibody with open-loop kinematic system are initially expressed in the augmented form

$$\begin{bmatrix} M & C^T & 0 \\ C & 0 & -H \\ 0 & -H^T & 0 \end{bmatrix} \begin{bmatrix} a \\ \lambda \\ \ddot{q} \end{bmatrix} = \begin{bmatrix} g \\ \gamma \\ Q \end{bmatrix} \quad (3)$$

where M is a block diagonal inertia matrix expressed in the Cartesian form, C is the body connectivity matrix, H

is a block diagonal joint influence coefficient matrix, a is the body Cartesian accelerations, λ is a vector of the Lagrange multipliers, $\ddot{q}$ is the second time derivative of joint variables, g is a vector of the externally applied loads, γ is the quadratic constraint derivatives, and Q is the generalized forces. The Cartesian accelerations and Lagrange multipliers are then eliminated from (3) to obtain the reduced equations

$$M_q \ddot{q} = Q \quad (4)$$

where M_q is the generalized mass matrix projected in the joint subspace and can be calculated as follows

$$M_q = H^T C^{-T} M C^{-1} H \quad (5)$$

and Q is the generalized force vector projected in the joint subspace and can be calculated as follows

$$Q \leftarrow Q + H^T C^{-T} (g - M C^{-1} \gamma) \quad (6)$$

This equation of motion (4) represents the smallest set of differential equations, and that form is similar to the Lagrangian form presented in (1). However, this form is limited to open-loop unconstrained mechanisms and therefore is suitable only for robotic type mechanisms. To illustrate limitations of the above equations, Figure 4 shows a graphical representation of the partial hydraulic excavator model in Figure 3, composed entirely of rigid bodies. The green and yellow nodes represent the rigid bodies and the solid arrows represent the idealized kinematic joints. To model a closed-loop mechanism, one of the loop joints has to be replaced by a stiff spring (chord joint). The spring stiffness values are tuned to represent the locked and free modes of the actual joint. The chord joints, represented by the blue arrows, form closed kinematic loops.

TomSim's evaluator and solver algorithms exploit the factored forms of (5) and (6) to optimally solve (4). But, as noted above, high frequencies from the chord joints reduce the effectiveness of the optimized algorithms and increase the simulation time. Also, the high frequencies resulting from the chord joints degrade the quality of the simulation results. In order to avoid the high frequencies resulting from the chord joints, constraint equations can be appended to equation (3).

EQUATION OF MOTION OF CONSTRAINED SYSTEM

The multibody system's equations of motion with appended constraints are typically represented as

$$\begin{bmatrix} M_q & J^T \\ J & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda_q \end{bmatrix} = \begin{bmatrix} Q \\ \gamma_q \end{bmatrix} \quad (7)$$

where M_q is the generalized mass matrix, J is the Jacobian matrix, and the other column matrices are similar to those described earlier. A model's constraint equations are appended to the reduced equations of motion in (3) to obtain (7).

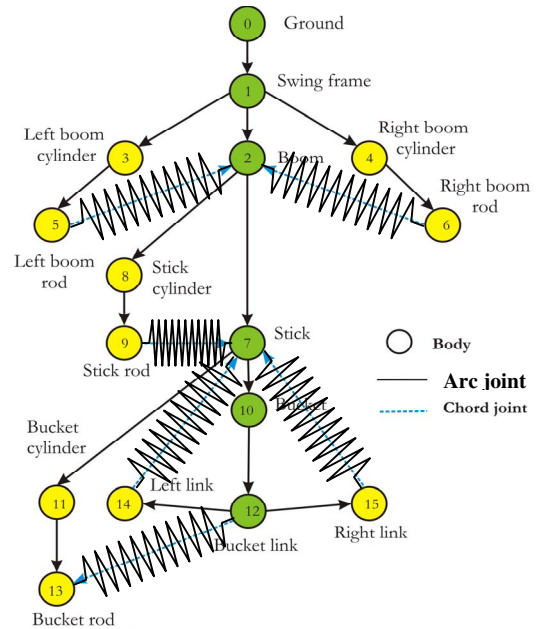


Figure 4 Spanning tree for the excavator model with stiff chord joint springs.

The coefficient matrix in the left hand side of (7) is often singular, and general-purpose sparse matrix solver algorithms are routinely used to analyze, factor, and solve the equations. Solving (7) directly is too expensive for our applications, so TomSim solver devised an alternative approach based on generalized coordinate partitioning. The factored forms of (5) and (6) used to obtain (4) play a significant role in TomSim evaluator and solver efficiency.

The generalized coordinate partitioning method [1] first analyzes the model topology and decomposes it into a number of kinematically uncoupled superelements, each with a much smaller Jacobian matrix. The spanning tree for the partial hydraulic excavator model, shown in Figure 5, is used to illustrate the process. As noted earlier, the black arrows represent the idealized kinematic joints, and the blue arrows represent the chord joints that form the kinematic loops. The main kinematic part of the model is partitioned into superelements, and represented by the uncoupled acceleration constraint equations as follows

$$\begin{bmatrix} \Phi_q^1 & \dots & 0 \\ \dots & \dots & \dots \\ 0 & \dots & \Phi_q^n \end{bmatrix} \begin{bmatrix} \ddot{q}^1 \\ \vdots \\ \ddot{q}^n \end{bmatrix} = \begin{bmatrix} \gamma^1 \\ \vdots \\ \gamma^n \end{bmatrix} \quad (8)$$

Each Jacobian matrix in (8) is factored into LU form using complete pivoting to partition the variables into