

# Simulating Flexible Multibody Vehicle Models in Real-Time

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The ever increasing availability of computing power is changing the role of multibody dynamics software. The conventional role of multibody dynamics software has been in an analysis role and not in a design role. It is often employed to assess failures of an already existing design with its primary purpose to generate loads. Loads which are applied to a finite element analysis model.

When applied in a design role it is usually not in a real-time or hardware-in-the-loop role. The fact is high fidelity multibody models particularly flexible models are too large and contain too high a frequency content to simulate in real-time. Despite this fact the automotive industry is pressing for the use of a single model across multiple departments. The use of a single model insures data consistency between departments and saves costs in the long run. The result is more sophisticated multibody models must be used in a real time role as well as an analysis role. Past studies [1, 2] have shown that it is feasible to run multibody models in a real-time environment. However, none of these models have used a flexible body. This paper will focus on techniques and methods needed to simulate complex flexible multibody models in real-time. The Virtual.Lab motion real-time solver will be employed in this paper.

The Virtual.lab Motion solver uses a set of Cartesian coordinates to model each rigid body in the model. Each rigid body center of gravity is located by three translations from the global reference and the set of Euler parameters are used to orient each rigid body in space. Predefined libraries of joints and constraints can be used to remove degrees of freedom from a model. Also, available are libraries of force elements such as bushings, tires and contact models.

Flexible bodies are modeled using a component mode synthesis technique [3]. A flexible body model of an individual part is built in a finite element package and a set of modes are extracted for use in the multibody model. The modes can be either static or normal modes or a combination. Like a rigid body a reference frame is attached to the flexible body this reference is located by the same set of coordinates used for a rigid body, Figure 1.

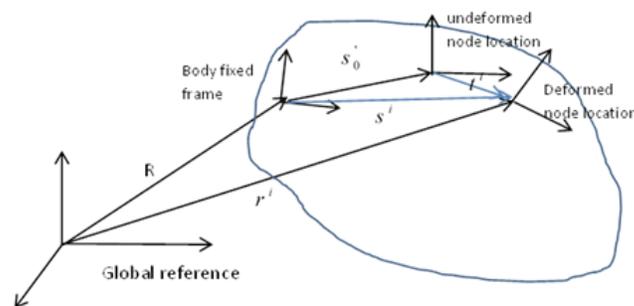


Figure 1: Flexible Body

The location of any node on the flexible body with respect to the flexible reference frame is a combination of 3 translational deformations,  $t^i$  and 3 rotational deformations,  $\theta^i$ .

$$\dot{t}^i = \xi_T^{i'} a \quad (1)$$

$$\theta^i = \xi_R^{i'} a \quad (2)$$

The vector,  $a$ , is the modal scale factors that become generalized coordinates in the multibody solver formulation while  $\zeta$  are the mode shapes. The equations of motion for a single flexible body becomes.

$$\sum_{i=1}^n m_i \begin{bmatrix} m_0 I & (As^i)_p & A \xi_T^{i'} \\ (As^i)_p & -4G^T \tilde{s}^i \tilde{s}^i G & 2G^T \tilde{s}^i \xi_T^{i'} \\ (A \xi_T^{i'})^T & -2(\xi_T^{i'})^T \tilde{s}^i G & (\xi_T^{i'})^T \xi_T^{i'} \end{bmatrix} \begin{bmatrix} \ddot{r} \\ \ddot{p} \\ \ddot{a} \end{bmatrix} + \sum_{i=1}^n \begin{bmatrix} 0 & 0 & 0 \\ 0 & 4G^T J^i G & 2G^T J^i \xi_R^{i'} \\ 0 & 2(\xi_R^{i'})^T J^i G & (\xi_R^{i'})^T J^i \xi_R^{i'} \end{bmatrix} \begin{bmatrix} \dot{r} \\ \dot{p} \\ \dot{a} \end{bmatrix} - \sum_{i=1}^n m_i \begin{bmatrix} -2[A_p s^i + \dot{A} t^i] \\ 2G^T (\tilde{s}^i \tilde{s}^i + \tilde{s}^i \dot{t}^i) \omega \\ (\omega^i)^T \xi_T^{i'} (2t^i - \tilde{s}^i \omega^i) \end{bmatrix} \\ - \sum_{i=1}^n m_i \begin{bmatrix} 0 \\ 2G^T (J^i \tilde{\omega} \dot{\theta}^i + \tilde{s}^i \dot{t}^i + \tilde{\omega} J^i \omega^i) \\ (\xi_R^{i'})^T (J^i \tilde{\omega} \dot{\theta}^i + \tilde{s}^i \dot{t}^i + \tilde{\omega} J^i \omega^i) \end{bmatrix} - \sum_{i=1}^n m_i \begin{bmatrix} 0 \\ 0 \\ \xi^T K \xi a - \xi^T D \xi \dot{a} \end{bmatrix} \quad (3)$$

In Eq. (3)  $G$  is a matrix of Euler parameters used to transform from local space to Euler parameter space. The finite element stiffness and damping matrices are  $K$  and  $D$  respectively. The inertia matrix of the body is  $J$  and the angular velocity is  $\omega$ . To achieve real-time a mass matrix case for a flexible body is employed that reduces out many of the mass invariant terms.

The real-time solver expresses the equations of motion in the following descriptor form.

$$\begin{aligned} \dot{q} - v &= 0 \\ M\dot{v} + \Phi_q^T \dot{\Psi} &= Q_a \\ \Phi_q v &= 0 \end{aligned} \quad (4)$$

$Q_a$  is the vector of applied forces,  $M$  the mass matrix and  $\Phi(q)$  are the constraints arising from joints connecting the bodies in the model. A Lagrange multiplier is used to append the constraints to the Newton-Euler equations of motion. A differential quantity  $\dot{\Psi}$  is used to represent the Lagrange multipliers because it along with the use of the velocity level constraint equations lowers the index of the equations of motion to one.

These equations can be numerically stiff therefore in the real-time analysis a fixed step, 2<sup>nd</sup>-order BDF method is applied. To make the system deterministic the iterations of the BDF method are fixed and the Baumgarte stabilization method is used to correct drift.

A fixed step BDF method will not be enough to achieve a deterministic real time solution with a turnaround time of 1 millisecond. One additional method required to achieve real-time of flexible real-time models is parallel computing. While computing power is increasing it is increasing mainly in terms of parallel computing power not necessarily in an overall increase in clock speed. Therefore, it is necessary to take advantage of parallel processing to speed up the simulations. For automotive analysis the vehicle is split into two halves, front and rear, a co-simulation between the front and rear is used.

This paper will discuss the implementation and use of these techniques on a full vehicle model executed in a real-time environment.

## References

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- [3] Yoo, S. W., Dynamics of Flexible Mechanical Systems Using Finite Element Lumped Mass Approximation and Static Correction Modes, Technical Report, 85-7, Center of Computer-Aided Design, 1985