



VEHICLE DYNAMIC MODELING AND SIMULATION: COMPARING A FINITE-ELEMENT SOLUTION TO A MULTI-BODY DYNAMIC SOLUTION

Paramsothy Jayakumar, PhD

Dynamics & Structures Modeling & Simulation
US Army RDECOM TARDEC
Warren, MI

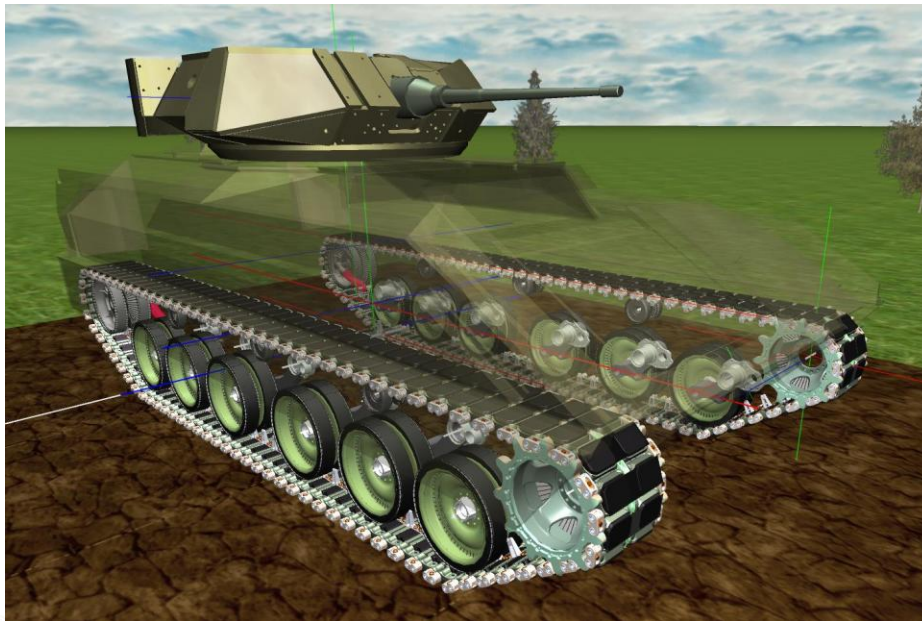
Tamer Wasfy, PhD

Advanced Science and Automation Corp.
Indianapolis, IN

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 06 AUG 2010		2. REPORT TYPE Briefing Charts		3. DATES COVERED 09-01-2010 to 14-07-2010	
4. TITLE AND SUBTITLE VEHICLE DYNAMIC MODELING and SIMULATION: COMPARING A FINITE-ELEMENT OT A MULTI-BODY DYNAMIC SOLUTION				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Paramsothy Jayakumar; Tamer Wasfy				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Advanced Science and Automation Corp.,9714 Oakhaven Ct.,Indianapolis,IN,46256-8101				8. PERFORMING ORGANIZATION REPORT NUMBER ; #21096	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) #21096	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES For 2010 GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM (GVSETS) AUGUST 17-19					
14. ABSTRACT briefing charts					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 23	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



- Army needs high-fidelity multibody dynamic modeling of wheeled and tracked vehicles for predicting:
 - Stability (going over a rough terrain at high-speed, lane change, etc.)
 - Mobility analysis (going over bumps and potholes).
 - Fatigue life and durability of various vehicle components.



- Two modeling and simulation approaches:
 - Traditional solution: Rigid/Flexible Multibody Dynamics (MBD) codes.
 - Alternate solution: Explicit Finite Element (FE) codes.
- Advantages of Explicit FE codes over MBD codes.
 - Multi-physics modeling such as fluid-structure interaction or thermal effects.
 - Same software environment to model flexible bodies and to predict stresses
 - However, accurate stress analysis requires refined mesh and takes significantly more CPU time.
 - Easily accommodate nonlinear material characteristics such as plasticity and fracture.
 - Can be easily parallelized.
 - Simulation time increases linearly with the DOFs.

- Disadvantages of explicit FE codes over MBD codes.
 - Most explicit FE codes use an incremental updated-Lagrangian solution formulation which can lead to solution drift.
 - Use inexpensive finite elements that use spurious modes control.
 - Calculated joint reaction forces exhibit high-frequency oscillations. MBD codes, on the other hand, produce accurate joint forces.
 - Integration time step (Δt) must be less than a critical time step for stability.
 - This requires a very small time step for stiff systems. MBD codes, on the other hand, can use implicit integrators that allow larger time steps.

- Benchmark the two modeling and simulation approaches.
 - Multibody dynamic code.
 - Explicit finite element code.
- Benchmark using two multibody dynamic systems.
 - A 7-link planar mechanism.
 - A spatial robotic manipulator.
- Comparisons are made of:
 - Body motion.
 - Joint constraint forces.
 - Conservation of energy.
 - CPU time.
- Conclusions are drawn regarding solution accuracy and efficiency of the two codes.



- Equations of motion:

$$M_K \ddot{x}_{Ki}^t = F_{s_{Ki}}^t + F_{a_{Ki}}^t$$

$$I_{Kij} \ddot{\theta}_{Kj}^t = T_{s_{Ki}}^t + T_{a_{Ki}}^t - \left(\dot{\theta}_{Ki}^t \times (I_{Kij} \dot{\theta}_{Kj}^t) \right)_{Ki}$$

- Integrated using trapezoidal explicit integration formula:

$$\dot{x}_{Kj}^t = \dot{x}_{Kj}^{t-\Delta t} + 0.5 \Delta t (\ddot{x}_{Kj}^t + \ddot{x}_{Kj}^{t-\Delta t})$$

$$\dot{\theta}_{Kj}^t = \dot{\theta}_{Kj}^{t-\Delta t} + 0.5 \Delta t (\ddot{\theta}_{Kj}^t + \ddot{\theta}_{Kj}^{t-\Delta t})$$

$$x_{Kj}^t = x_{Kj}^{t-\Delta t} + 0.5 \Delta t (\dot{x}_{Kj}^t + \dot{x}_{Kj}^{t-\Delta t})$$

$$\Delta \theta_{Kj}^t = 0.5 \Delta t (\dot{\theta}_{Kj}^t + \dot{\theta}_{Kj}^{t-\Delta t})$$

$$R_K^t = R_K^{t-\Delta t} R(\Delta \theta_{Ki}^t)$$

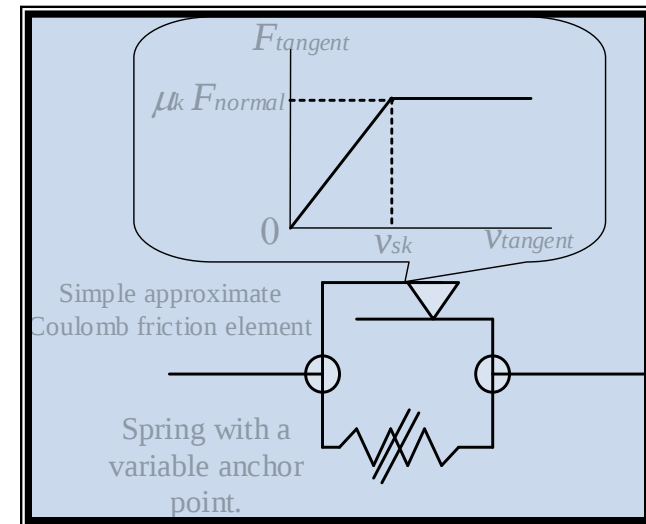


- Constraint modeling.
 - Penalty formulation for modeling normal contact/joint forces.

$$F_{c_j} = (k_p |\vec{d}| + c_p \hat{d}_i \dot{\hat{d}}_i) \hat{d}_j$$
$$d_i = x_{p1_i}^t - x_{p2_i}^t$$

where k_p : penalty stiffness, c_p : penalty damping

- Friction model.
 - Asperity-spring friction model is used to model joint and contact friction.





- Equations of motion :

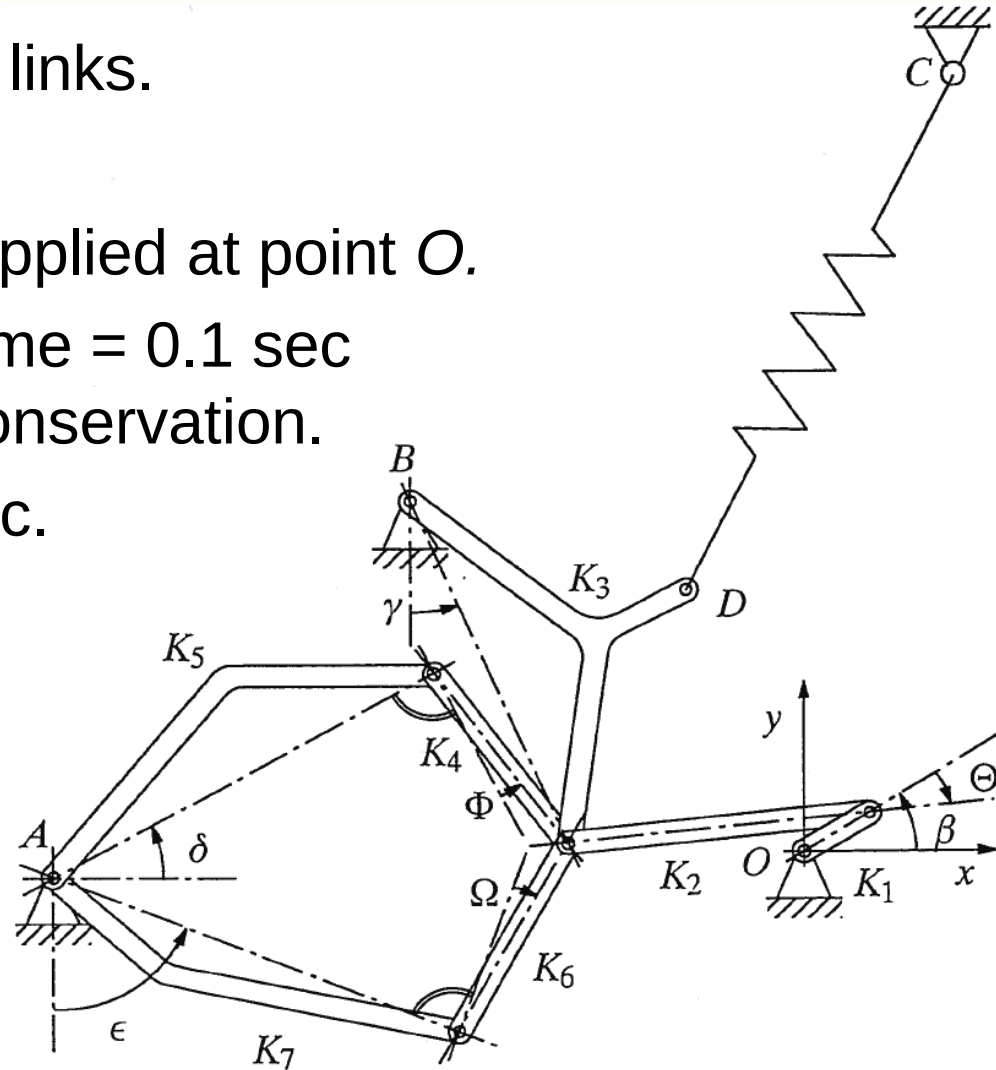
$$\begin{bmatrix} M & \frac{\partial \Phi^T}{\partial q} \\ \frac{\partial \Phi}{\partial q} & 0 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \lambda \end{Bmatrix} = \begin{Bmatrix} Q \\ \gamma \end{Bmatrix}$$

- Constraint equations: $\Phi(q, t) = 0 \quad \frac{\partial \Phi}{\partial q} \dot{q} = \nu$
- Forms a set of Differential-Algebraic Equations (DAEs).
- Solved using implicit integration methods such as the Backward Differentiation Formula.
 - Can take much larger time step than explicit methods.
 - Very advantageous for stiff systems.
 - Time step is only dictated by desired solution accuracy.

Benchmark Problem 1: 7-Link Planar Mechanism



- 2D mechanism with 7 rigid links.
- 1 DOF system.
- Driven by a motor torque applied at point O.
 - Torque is removed at time = 0.1 sec to assess the energy conservation.
- Total solution time = 0.5 sec.



Benchmark Problem 1: 7-Link Planar Mechanism

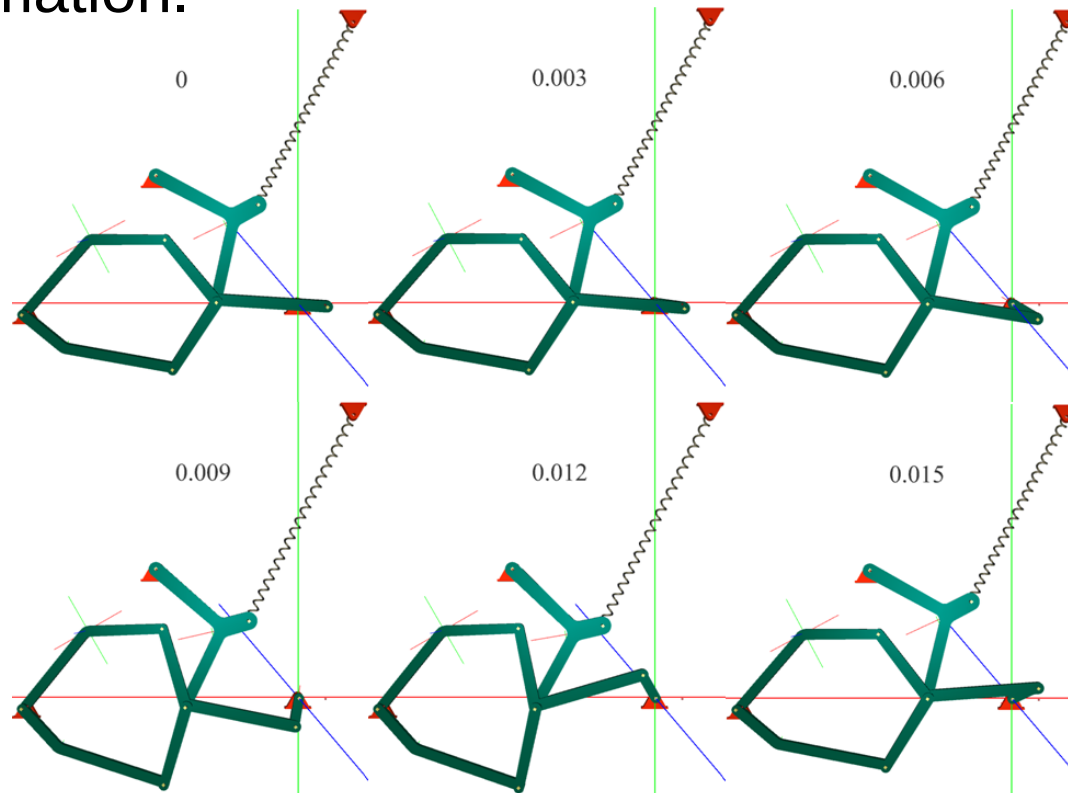
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- Time step / CPU time comparison.
- Animation.

	MBD	FE	FE
Time step (s)	1.0E-5	0.4E-5	0.1E-5
CPU time (s)	20.875	4.955	19.820
Position/velocity error Tolerance	1E-3	-	-

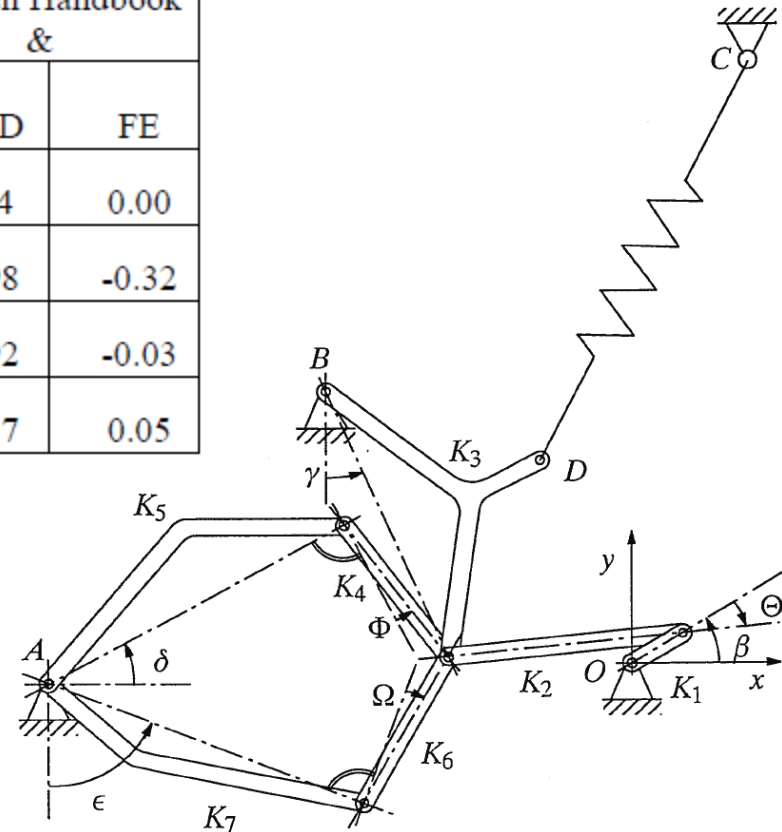


Benchmark Problem 1: 7-Link Planar Mechanism



- Link K1 rotation angle comparison.

Time (s)	Beta (rad)			% Difference between Handbook &	
	Handbook [3]	MBD	FE	MBD	FE
0.000E+00	-6.1994E-02	-6.2017E-02	-6.19953E-02	0.04	0.00
5.000E-03	2.10881E-01	2.06715E-01	2.10215E-01	-1.98	-0.32
1.000E-02	2.16040E+00	2.14057E+00	2.15981E+00	-0.92	-0.03
1.500E-02	5.65556E+00	5.64598E+00	5.65841E+00	-0.17	0.05

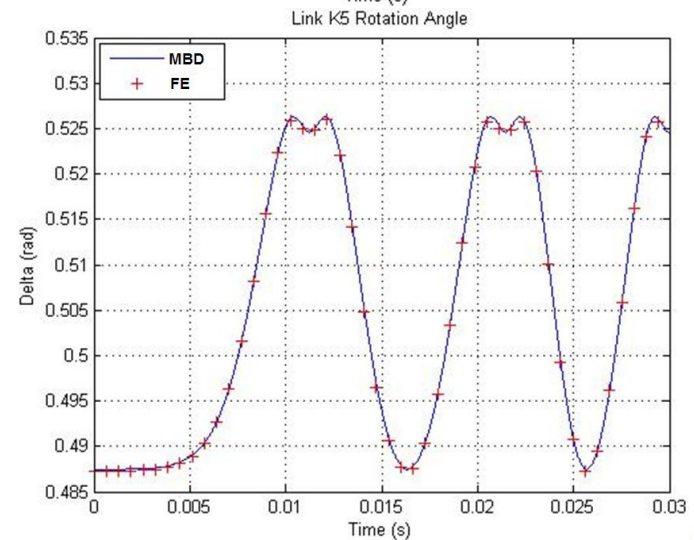
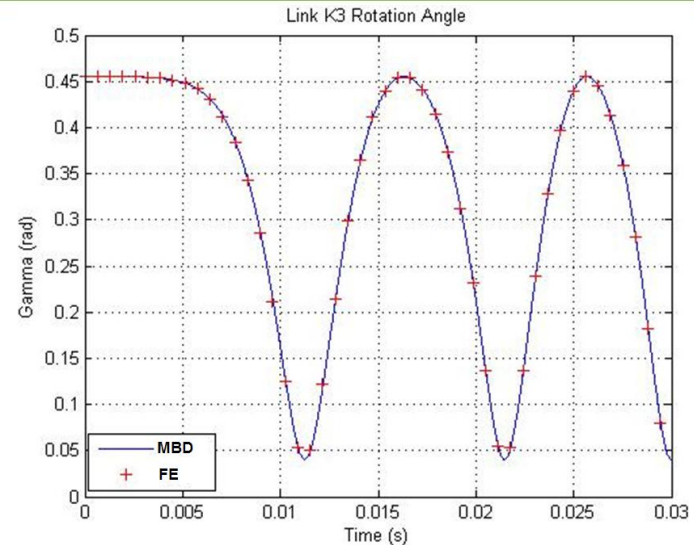
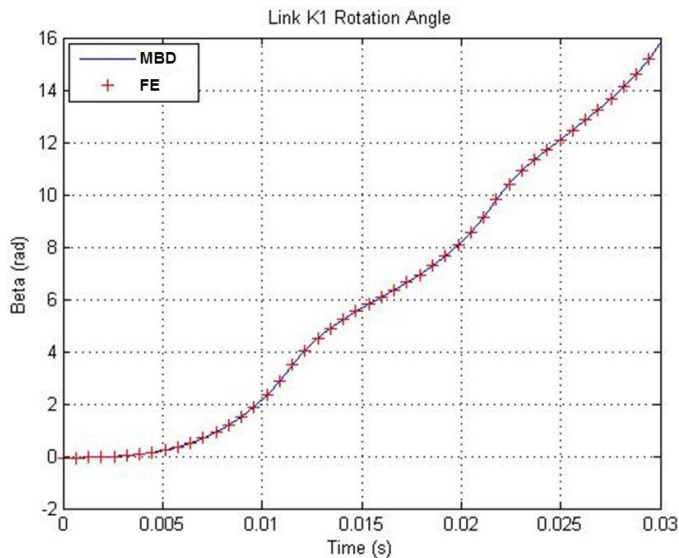


Benchmark Problem 1: 7-Link Planar Mechanism

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MODELING AND SIMULATION, TESTING AND VALIDATION

- Link rotation angles comparison

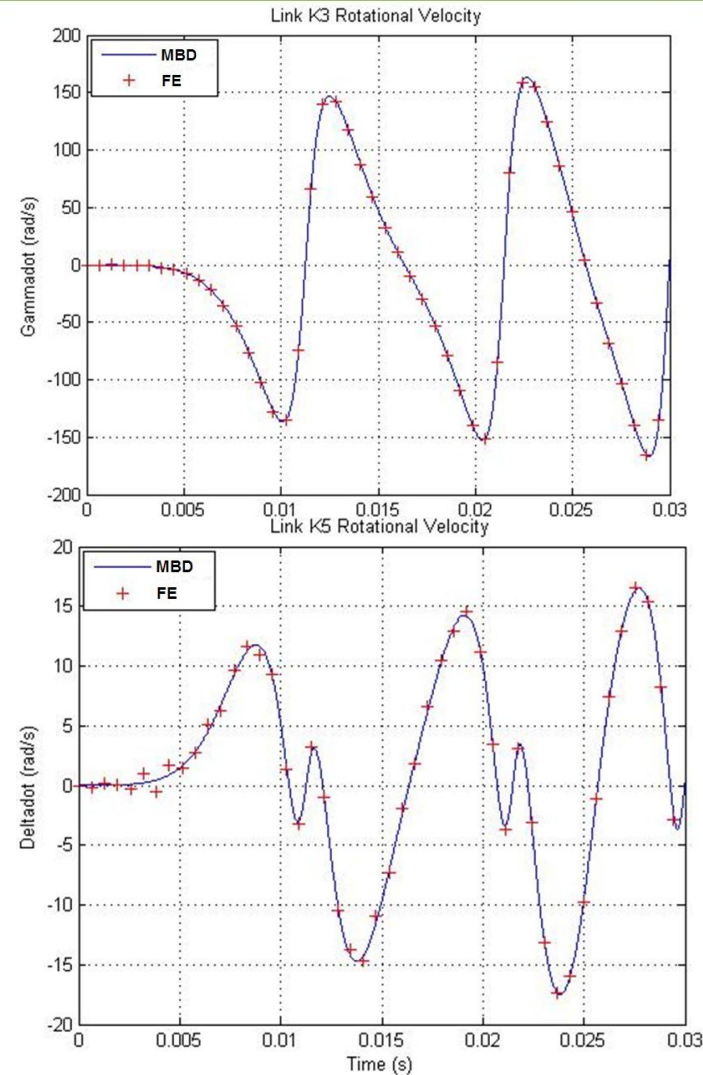
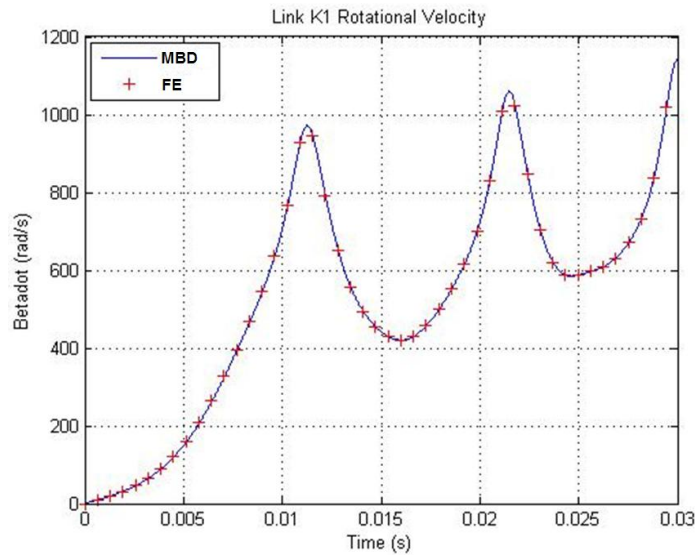


Benchmark Problem 1: 7-Link Planar Mechanism

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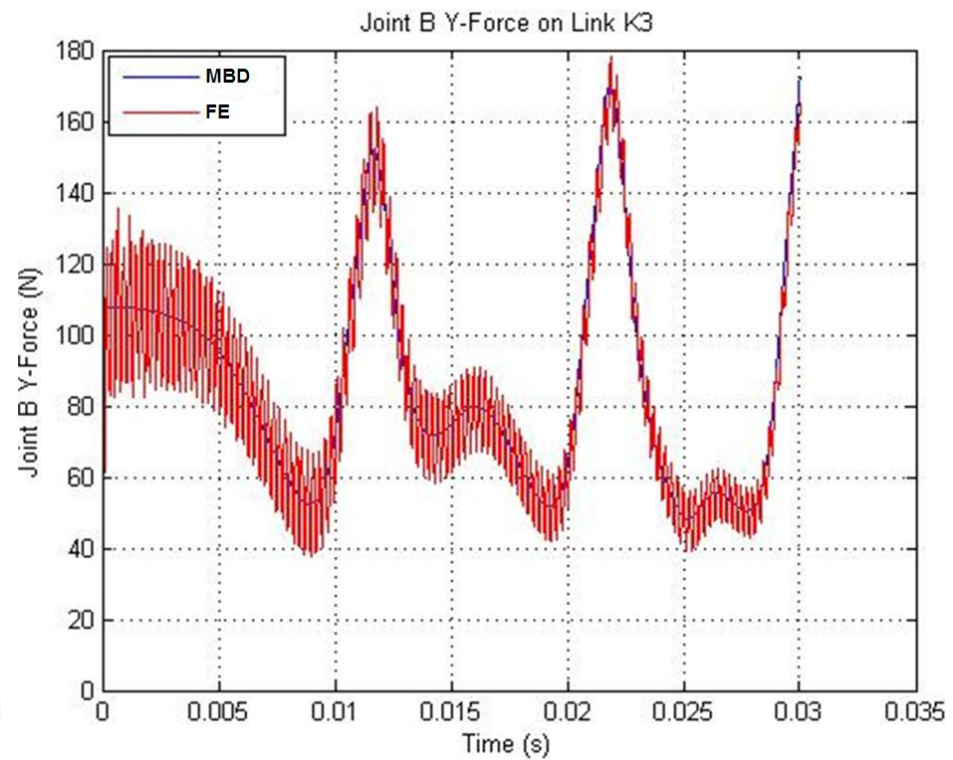
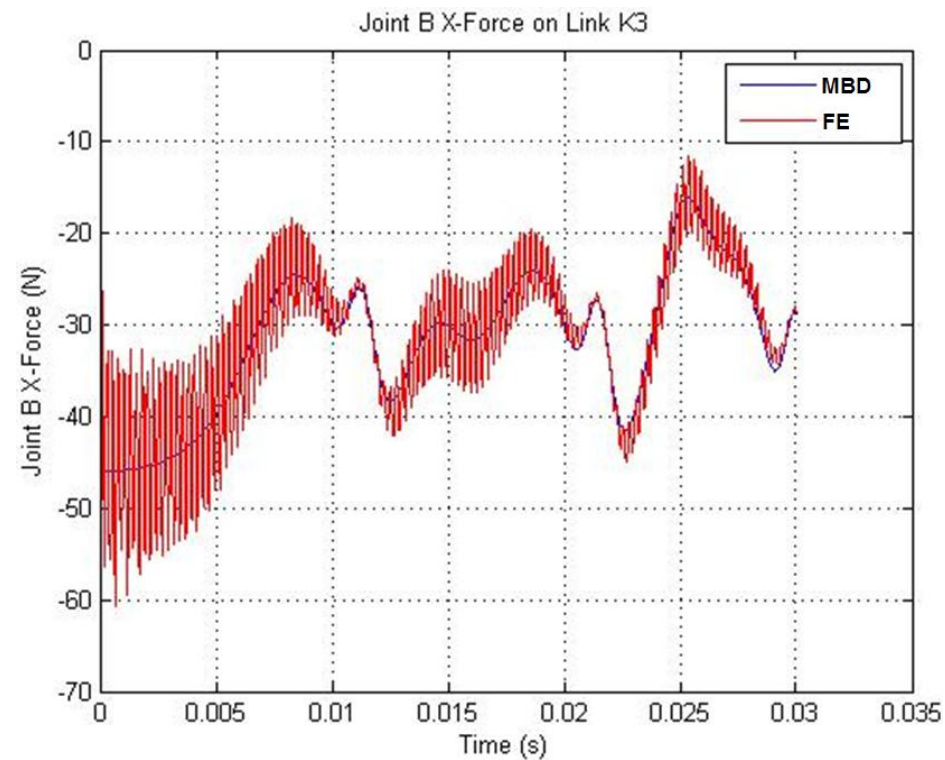
- Link velocities comparison.



Benchmark Problem 1: 7-Link Planar Mechanism



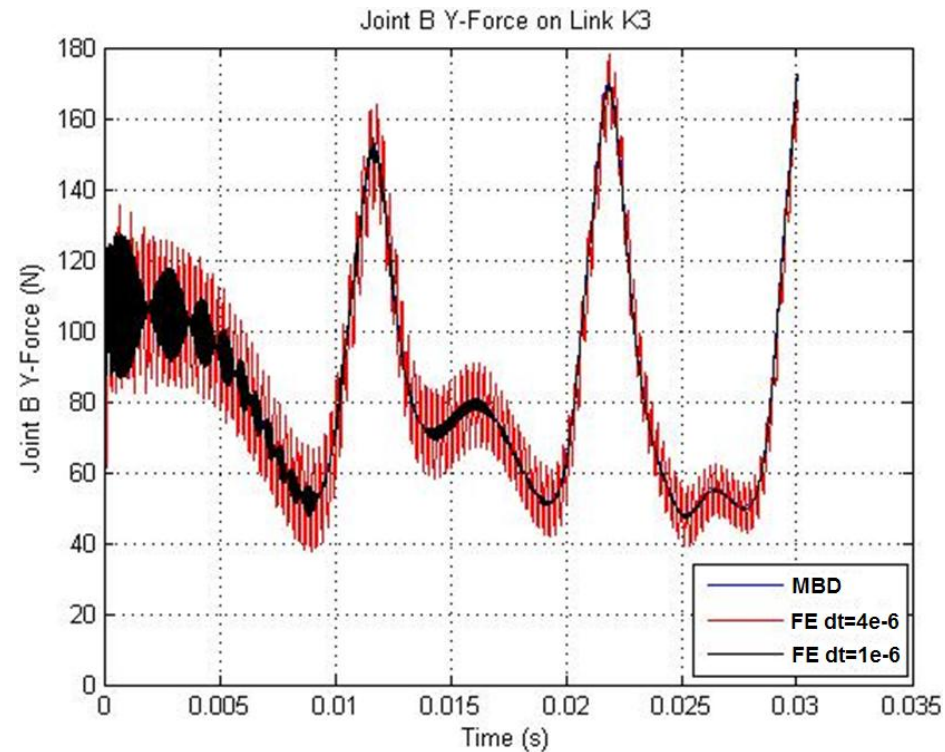
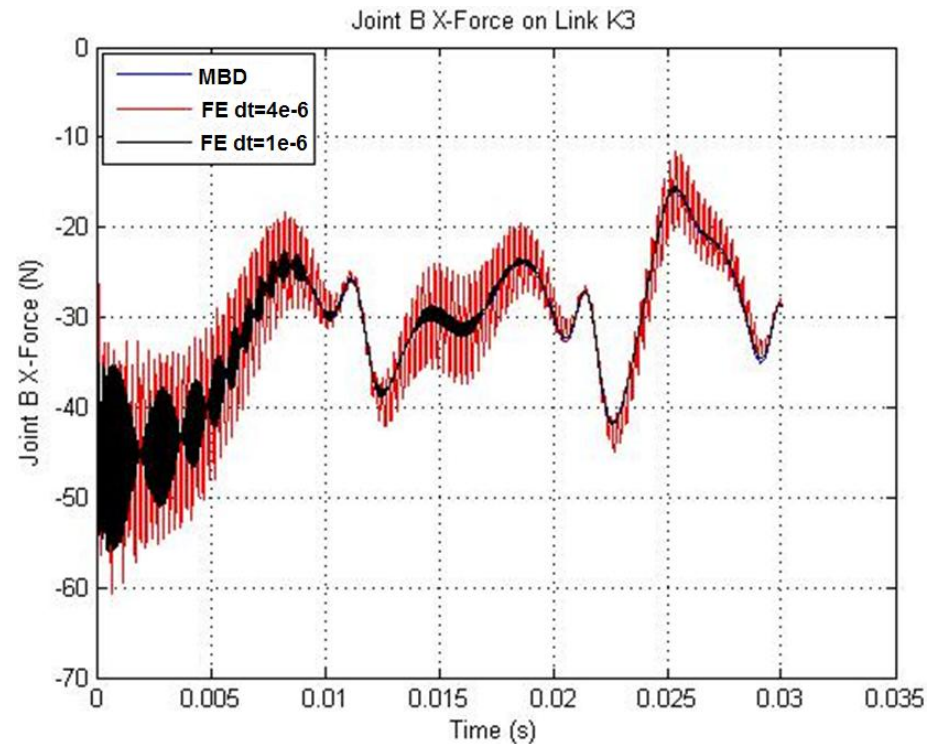
- Joint force comparison.



Benchmark Problem 1: 7-Link Planar Mechanism



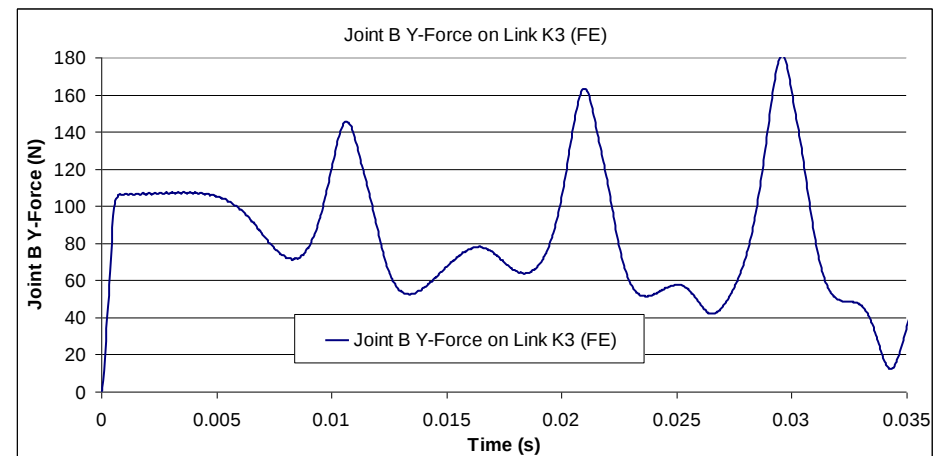
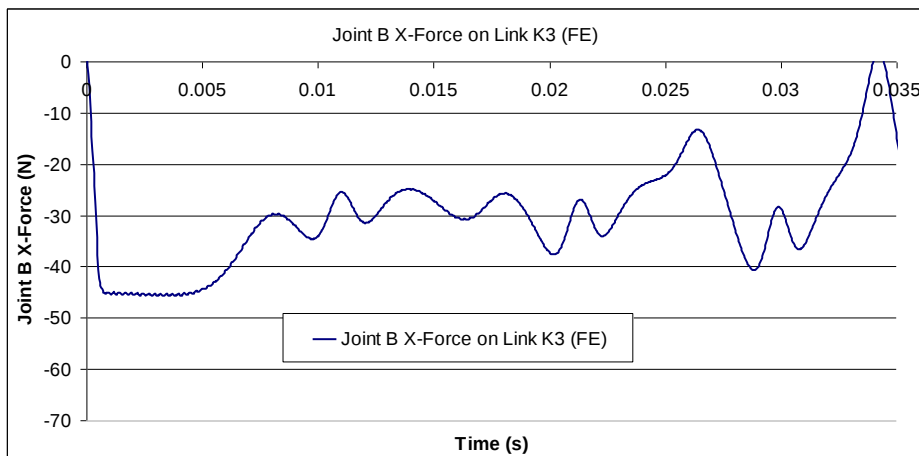
- Effect of FE time step on joint forces.



Benchmark Problem 1: 7-Link Planar Mechanism



- FE joint force with ramped applied torque and spring pre-load.

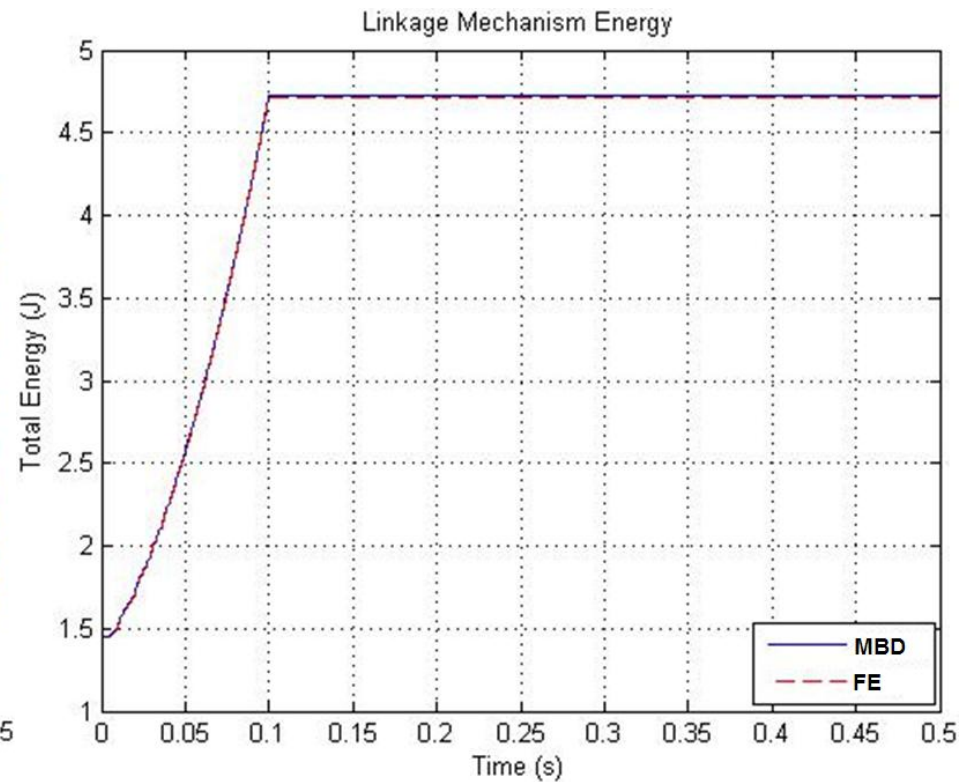
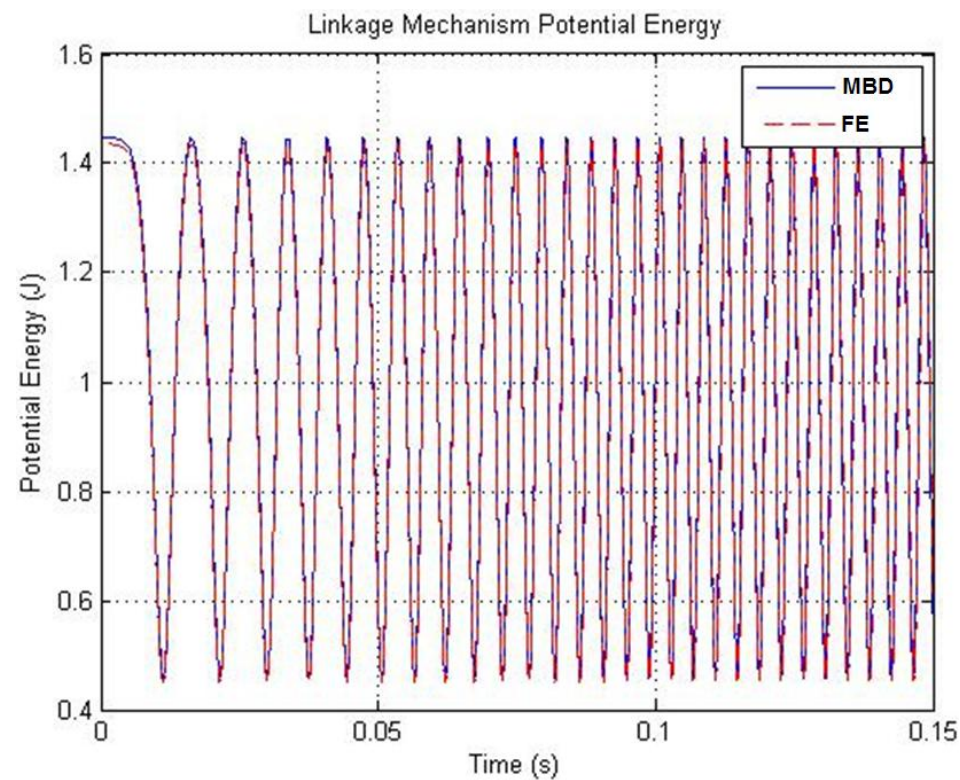


FE: $\Delta t = 0.4\text{E-}5$

Benchmark Problem 1: 7-Link Planar Mechanism



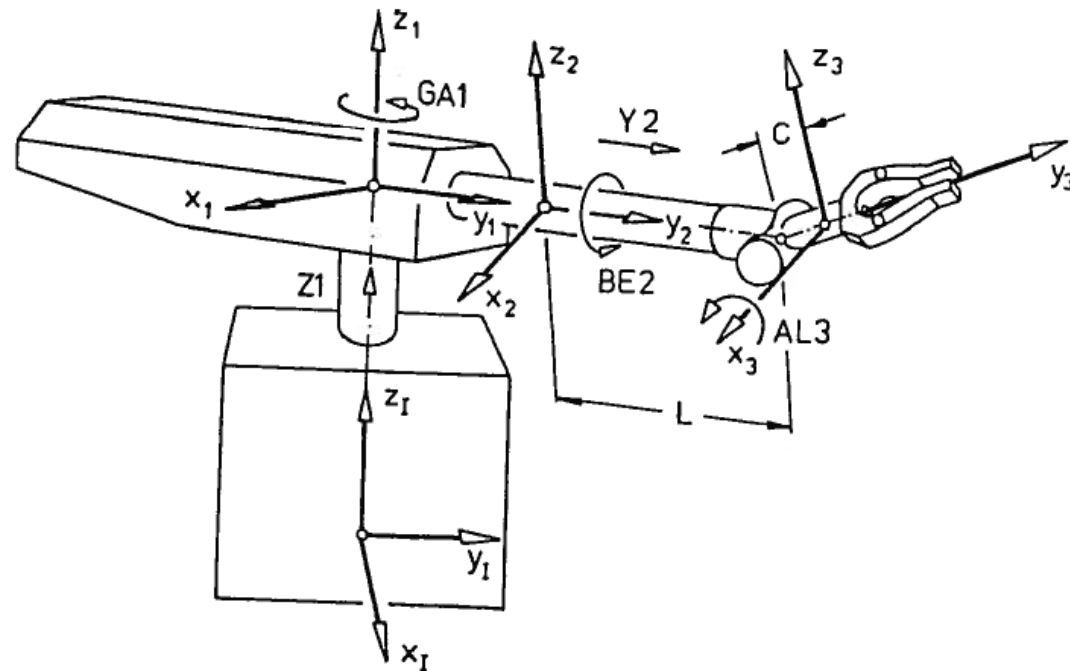
- Energy comparison.



Benchmark Problem 2: Spatial Robotic Manipulator



- 3 rigid bodies connected using cylindrical and revolute joints.
- 5 DOF system.
- External loads: gravity and prescribed joint actuator forces/torques.
- End effector traces a straight line with a trapezoidal velocity profile.
- Total solution time = 2.0 sec.



Benchmark Problem 2: Spatial Robotic Manipulator



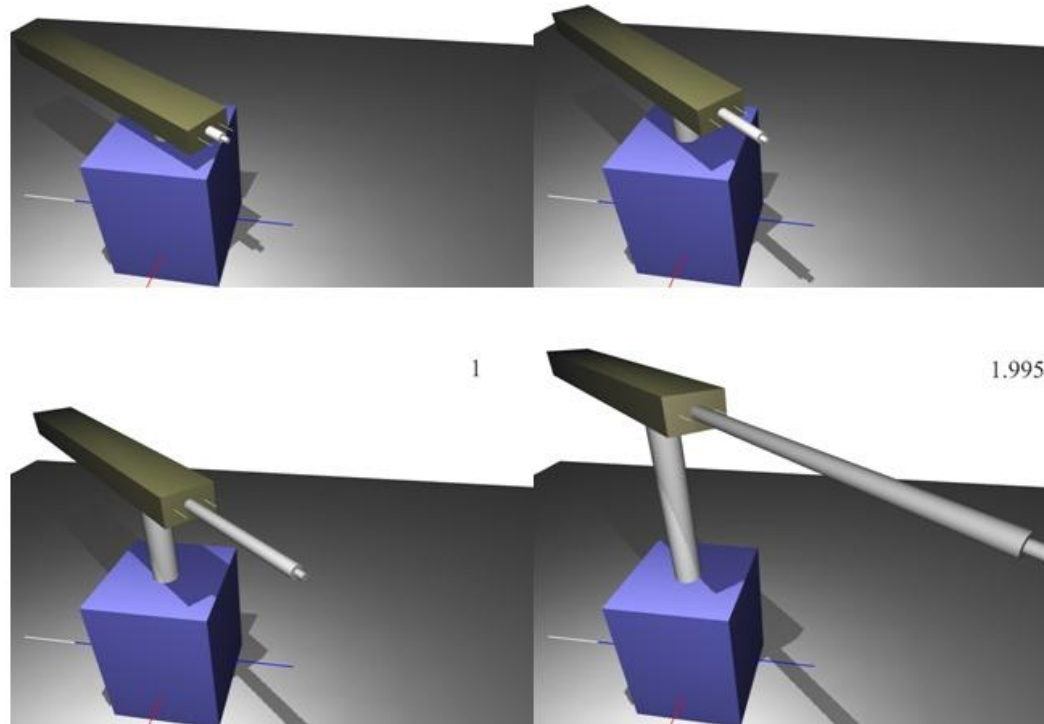
- Time step / CPU time comparison.

	MBD	FE
Time step (s)	0.01	3.75E-5
CPU time (s)	0.172	1.29

0

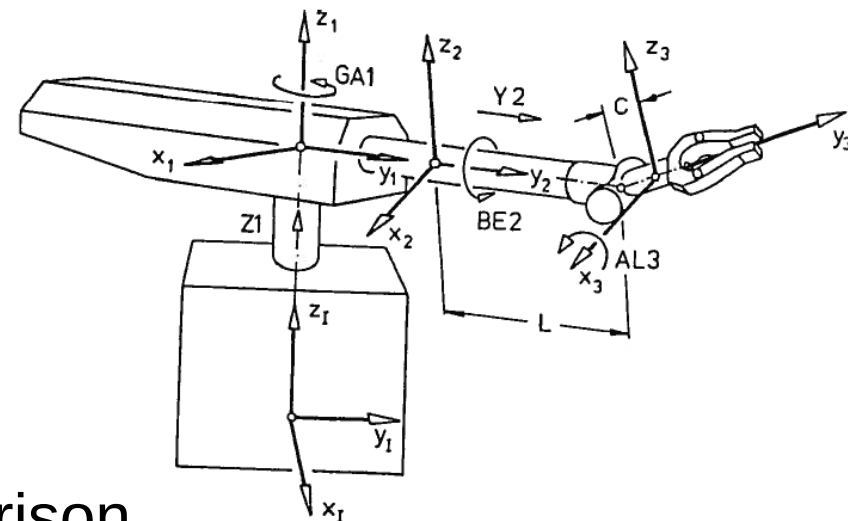
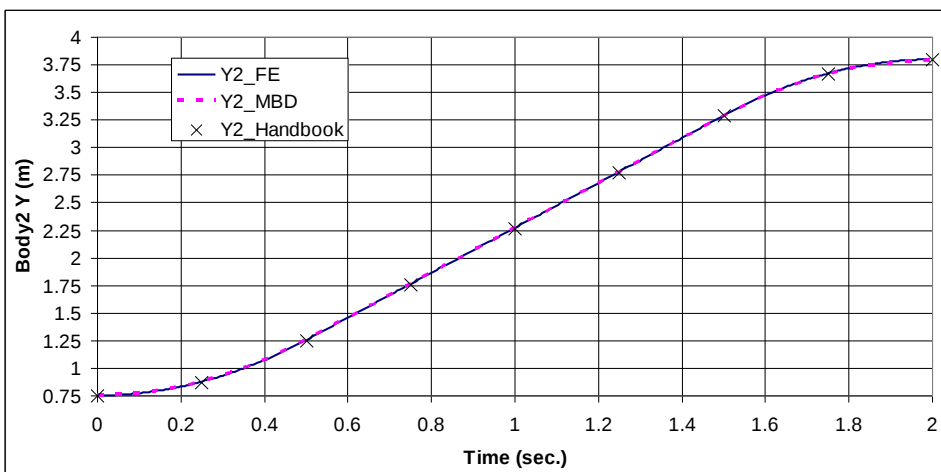
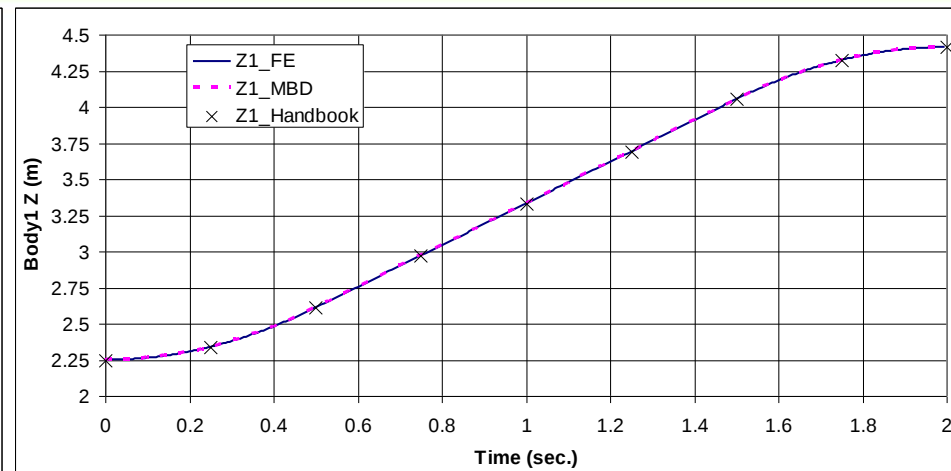
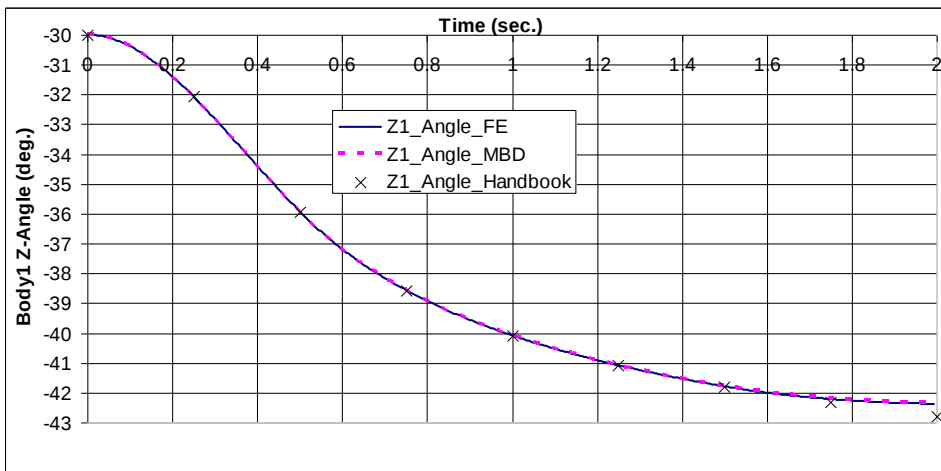
0.5

- Animation.



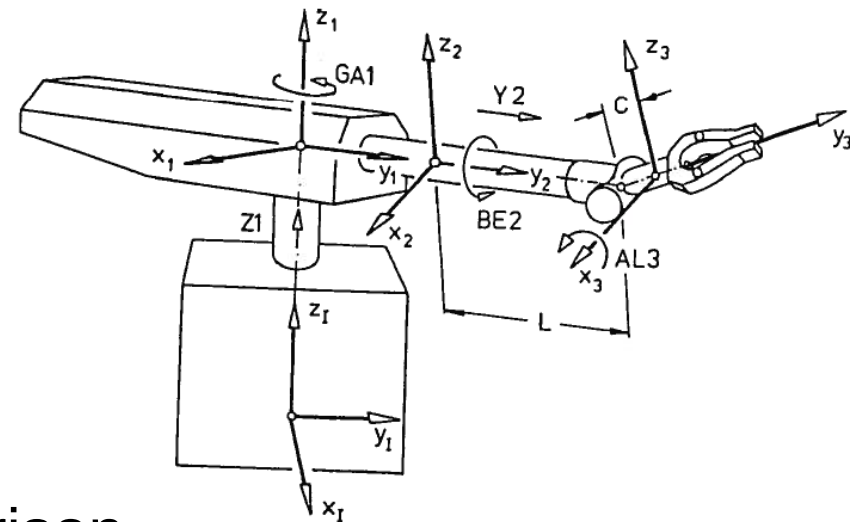
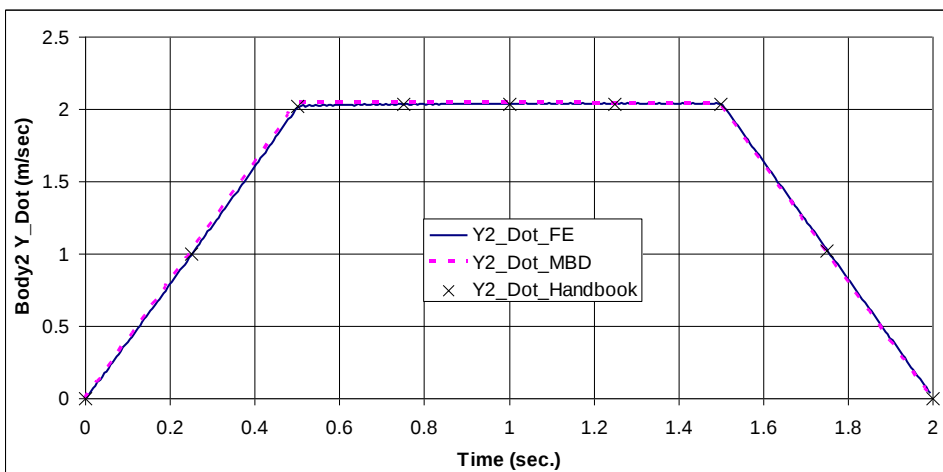
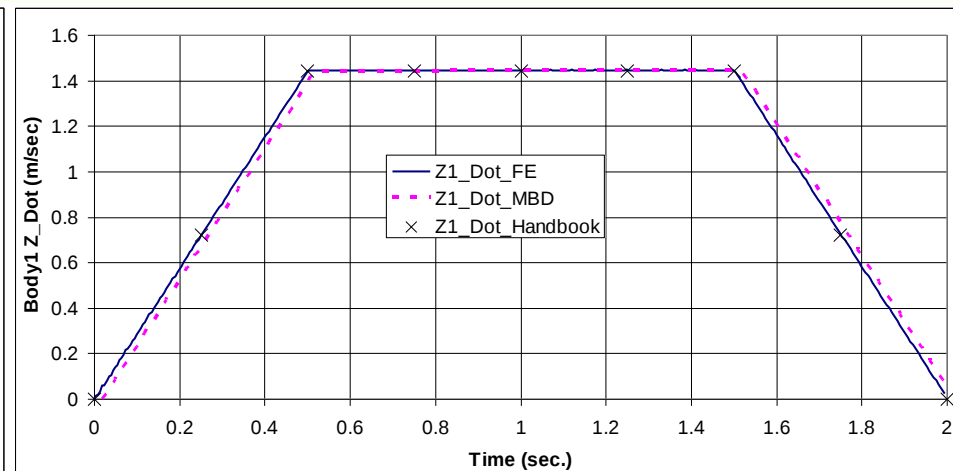
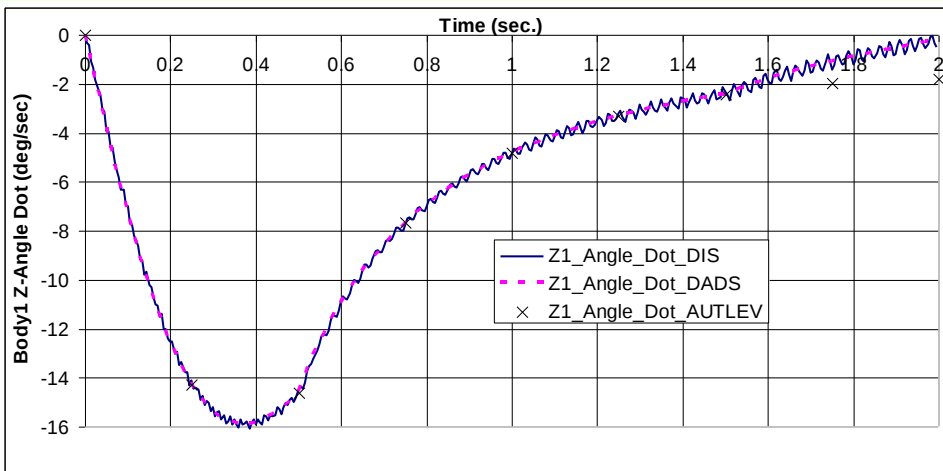
Benchmark Problem 2: Spatial Robotic Manipulator

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• Manipulator Position Comparison

Benchmark Problem 2: Spatial Robotic Manipulator

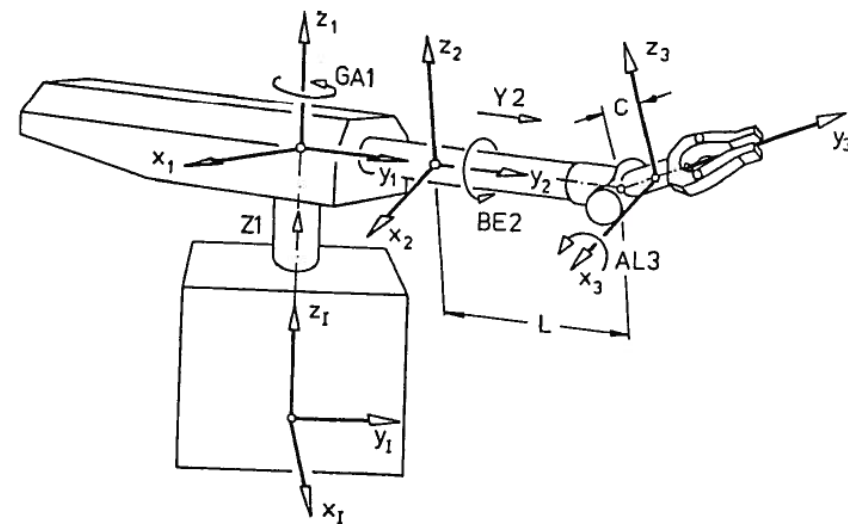
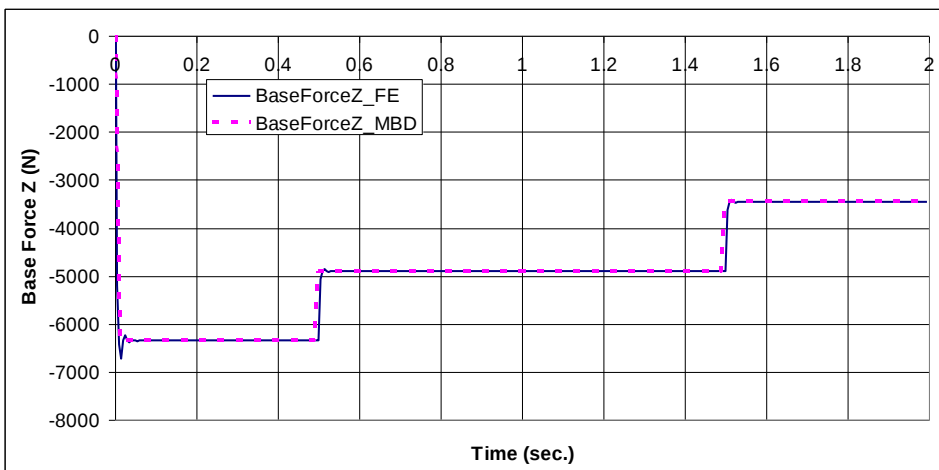
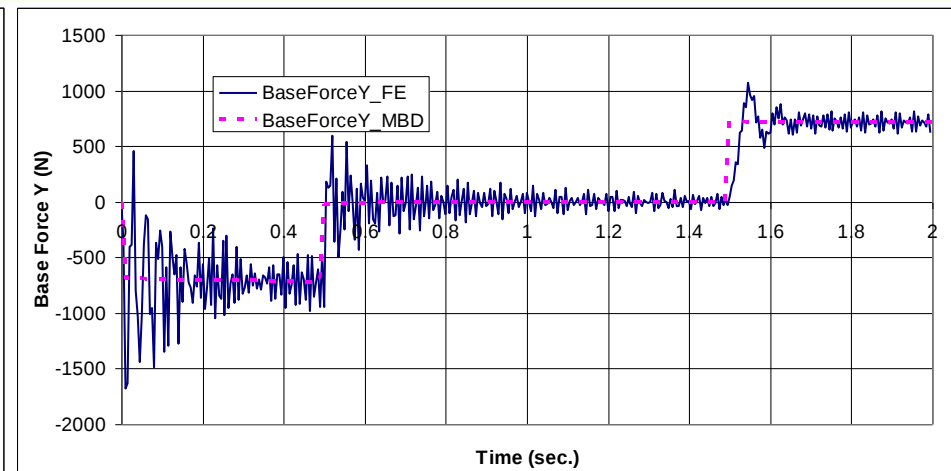
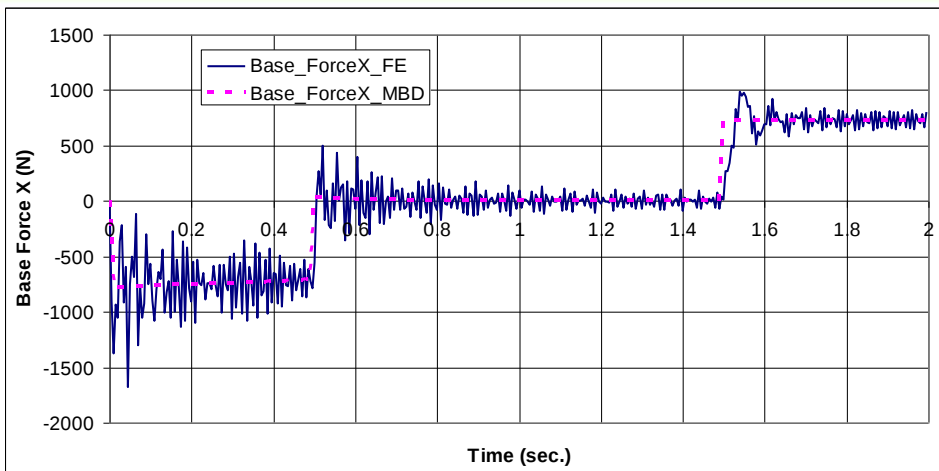


• Manipulator Velocity Comparison

Benchmark Problem 2: Spatial Robotic Manipulator

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• Manipulator Joint Force Comparison



Conclusions



- Two multibody dynamics benchmark problems were solved using
 - an explicit finite-element code and
 - an implicit multibody dynamics code.
- The two codes predict the same system motion.
- Joint reaction forces predicted by FE code have high-frequency oscillations due to the penalty method used.
- To eliminate high-frequency force oscillations when using FE code, applied forces/moments must be continuous and the simulation should start from static equilibrium.
- Implicit MBD codes are computationally more efficient than Explicit FE codes for stiff MBD systems.