MultiBody Systems Benchmark in OpenSim (MBS-BOS) - User Manual

Release 2.0

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Part I

MBS-BOS

MBS-BOS package is a set of programs that implement the MultiBody Systems (MBS) Benchmark *[GDLC06]* using the OpenSim *[DAA+07]* APIs.

The first objective is to assess OpenSim performances in simulating mechanical and robotic devices both in terms of accuracy and solving time.

The second objective is to provide C++ solutions for common problems that can be found in the implementation of simulations of multi-body systems.

If you use MBS-BOS for research work, please cite:

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L. Tagliapietra, M. Vivian, R. Caracciolo, and M. Reggiani.  Evaluation of
the biomechanical simulator OpenSim on a multi-body system benchmark.  In
Proceedings of the 2015 ECCOMAS Thematic Conference on Multibody Dynamics,
Barcelona, July 2015 (2015)
```

Part II

Latest Version

MBS-BOS is an open project, released under GNU General Public License and hosted in GitHub:

https://github.com/RehabEngGroup/MBSbenchmarksInOpenSim

A PDF version of this documentation can be found also on the SimTK.org page of this project:

https://simtk.org/home/mbs_bos

Part III

Benchmark Problems

CHAPTER

ONE

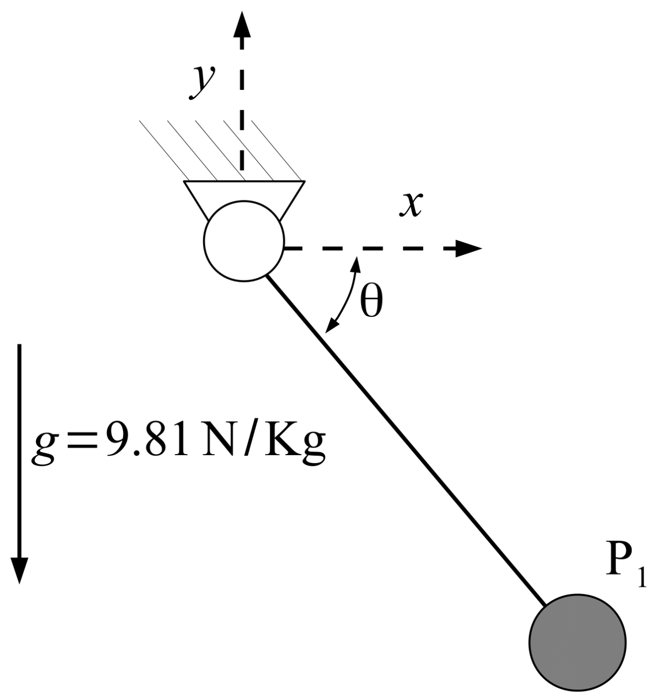
MBS BENCHMARK A01: SIMPLE PENDULUM

1.1 Benchmark Objective

The **A01** MBS benchmark problem is a simple planar pendulum. It is proposed as a demonstration example.

1.2 Benchmark Description

The Simple Pendulum is a planar mechanism composed of a point mass that is linked to the ground through a rigid massless bar.



The following table reports the system configuration: the only force applied to the mechanism is the gravity.

System Properties and Configuration	
P_1 mass	1.0 Kg
Bar length	1.0 m
Bar mass	0.0 Kg
$\theta(0)$	π rad
$\dot{\theta}(0)$	0.0 rad/s

1.3 Results

The dynamic simulation of the **A01** benchmark was executed for 10s. In the initial position, the system is horizontal with P_1 x-coordinate equals to -1.0 m and y-coordinate equals to 0.0 m. The first figure shows the variation of mechanical energy in the system, defined as sum of potential and kinetic energy, from the initial condition. Since no dissipation is present in the problem, variation should be zero. The second figure, instead, compares the outputs of the OpenSim-based simulation with the benchmark references available from *[GDLC06]*.

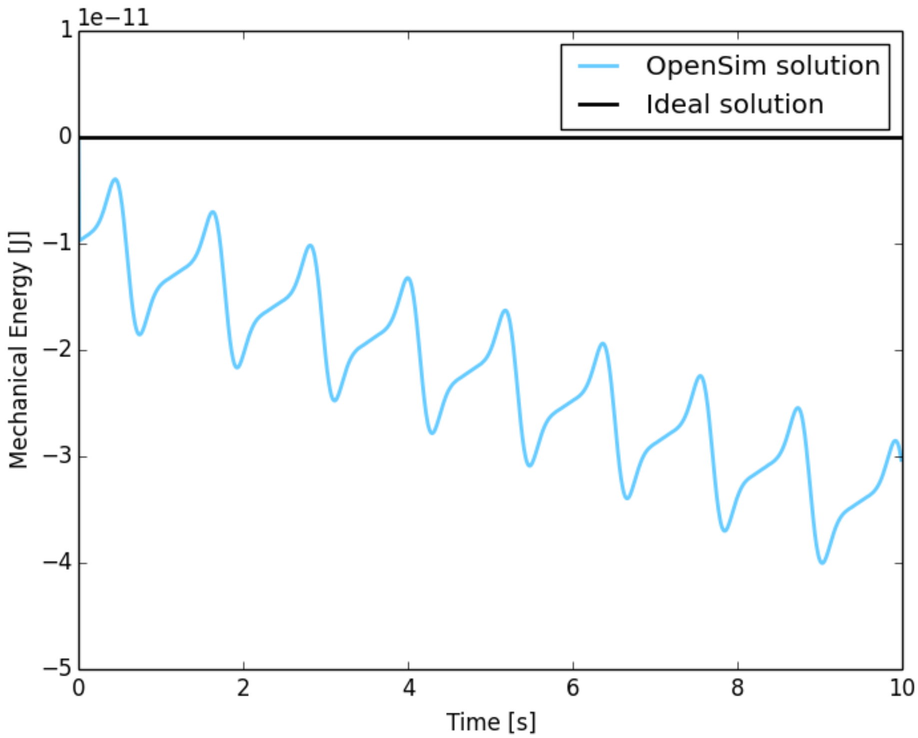


Fig. 1.1: Mechanical variation during simulation period from the initial condition. Theoretical variation (black line) and simulated one (blue line).

1.3.1 Computational Performances

To compute the simulation the developed implementation required 0.637 seconds.

Results obtained using an Intel Core i5-4570 @ 3.2 GHz computer running Windows 8.1 64-bit. OpenSim official release used: 3.2.

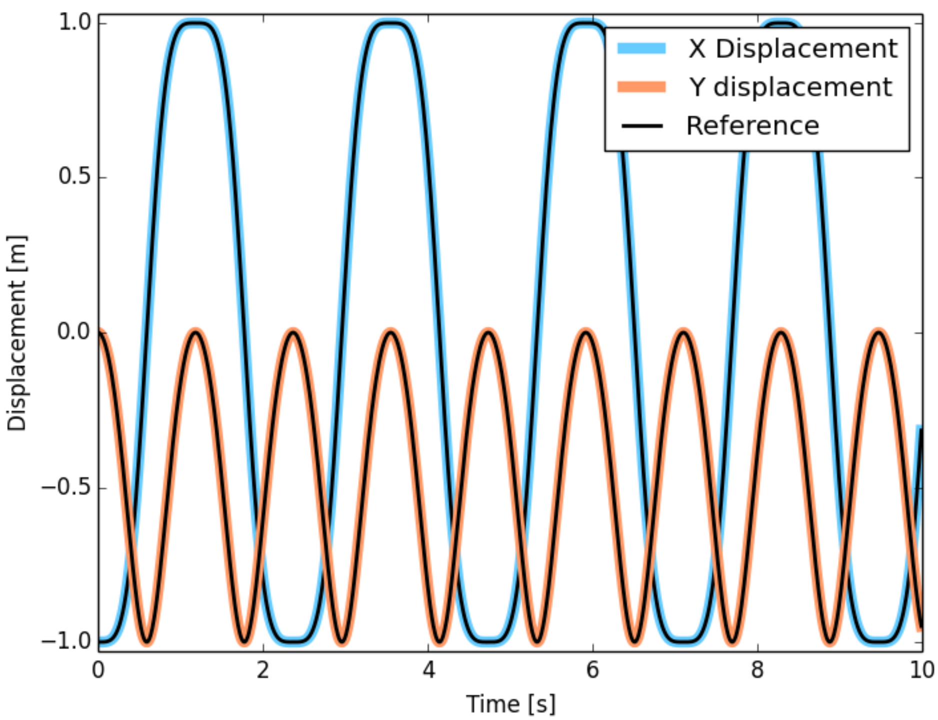


Fig. 1.2: Displacement of reference point P_1 in OpenSim simulation (colored lines) and MBS benchmark reference (black dashed lines).

Comparision with other dynamic engines has been conducted submitting the obtained results to the benchmark collaborative library. Click here[1] to see the comparison results.

1.4 Videos

Video of the problem simulated in OpenSim is available at https://youtu.be/TZZkVR39IH8

1.5 Download

- Simple Pendulum on MBS Benchmark library available at: http://goo.gl/eiygbC
- OpenSim implementation available at: http://goo.gl/R9tl3z
- Video of Simple Pendulum simulated in OpenSim available at: https://youtu.be/TZZkVR39IH8

[1] http://goo.gl/eiygbC

CHAPTER

TWO

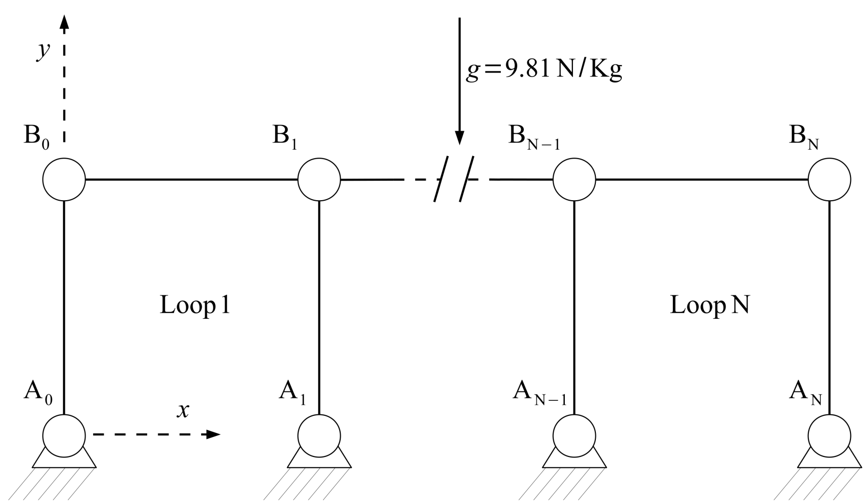
MBS BENCHMARK A02: N-FOUR-BAR MECHANISM

2.1 Benchmark Objective

The **A02** MBS benchmark problem is a common example of a mechanism which undergoes singular configuration.

2.2 Benchmark Description

The N-four-bar mechanism is a common example of a mechanism which undergoes singular configuration. The system has N four-bar windows composed of 2N+1 links. It is an extension of the two four-bar mechanism proposed in *[BA94]*. When the mechanism reaches the horizontal position, the number of the degrees of freedom instantaneously increase from 1 to N+1. Gravity acts on the negative y direction.



The following table reports the initial configuration of the system.

System Properties and Configuration	
N	2
Link mass	1.0 Kg
Link length	1.0 m
$\dot{B}_0x(0)$	1.0 m/s

2.3 Results

The dynamic simulation of the **A02** benchmark was executed for a period of 10 seconds. The starting position of the simulation is shown in the previous picture with an initial speed for the point B_0 in the positive x-direction of 1 m/s.

The accuracy of the simulation has been measured as the variation in the mechanical energy from the initial condition. Mechanical energy defined as the sum of potential and kinetic energy. Since no dissipation phenomena is included in problem definition, theoretical value for mechanical energy variation shoud be zero.

Additional evaluation has been conducted comparing the simulated displacement of the point B_0, with the reference solution provided by the problem authors *[GDLC06]*.

The simulation with OpenSim perfectly matches the reference values.

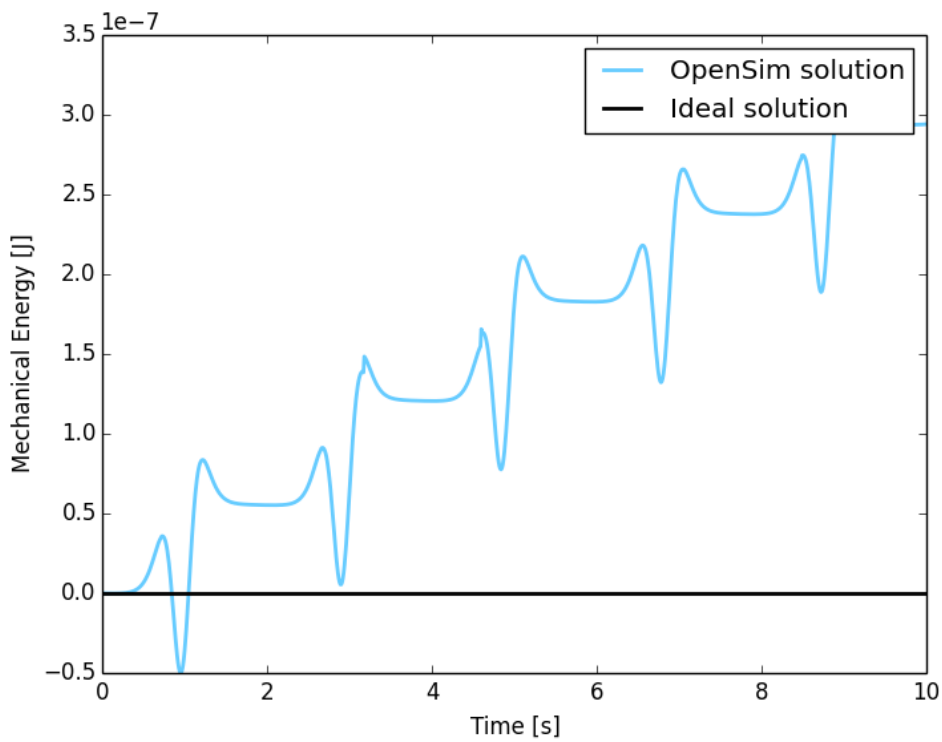


Fig. 2.1: Mechanical energy variation during simulation period from the initial condition. Theoretical variation (black line) and simulated one (blue line).

2.3.1 Computational Performances

To compute the simulation the developed implementation required 0.455 seconds.

Results obtained using an Intel Core i5-4570 @ 3.2 GHz computer running Windows 8.1 64-bit. OpenSim official release used: 3.2.

Comparision with other dynamic engines has been conducted submitting the obtained results to the benchmark collaborative library. Click here[1] to see the comparison results.

[1] http://goo.gl/c50tLg

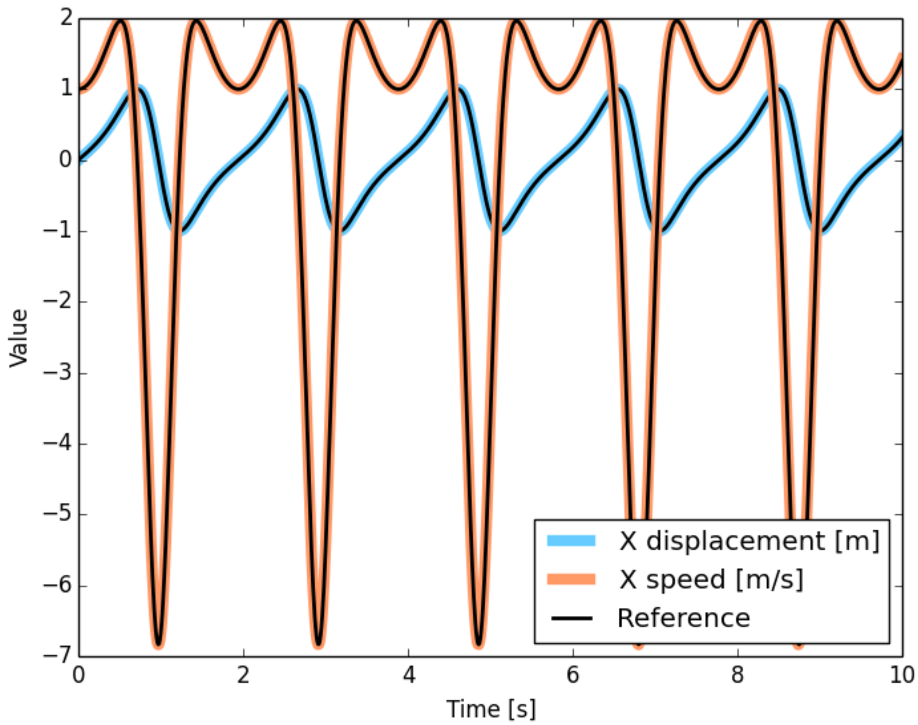


Fig. 2.2: Displacement of reference point B_0 in OpenSim simulation (colored lines) and MBS benchmark reference (black dashed lines).

2.4 Videos

Video of the problem simulated in OpenSim is available at https://youtu.be/eSesPhGIhco

2.5 Download

- N-four-bar mechanism on MBS Benchmark library available at: http://goo.gl/c50tLg
- OpenSim implementation available at: http://goo.gl/R9tl3z
- Video of N-four-bar mechanism simulated in OpenSimn available at: https://youtu.be/eSesPhGIhco

CHAPTER

THREE

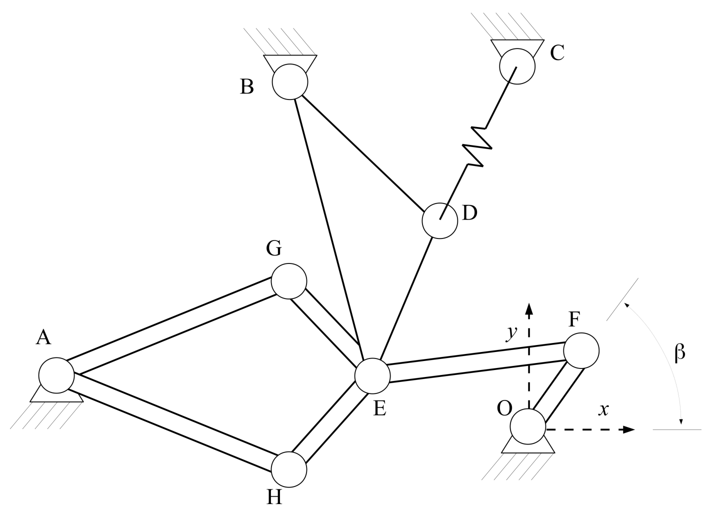
MBS BENCHMARK A03: ANDREW'S SQUEEZER MECHANISM

3.1 Benchmark Objective

The **A03** MSB benchmark problem has a very small time scale, thus making it difficult to simulate for solvers that cannot reach small time steps (below 1 ms) *[GDLC06]*.

3.2 Benchmark Description

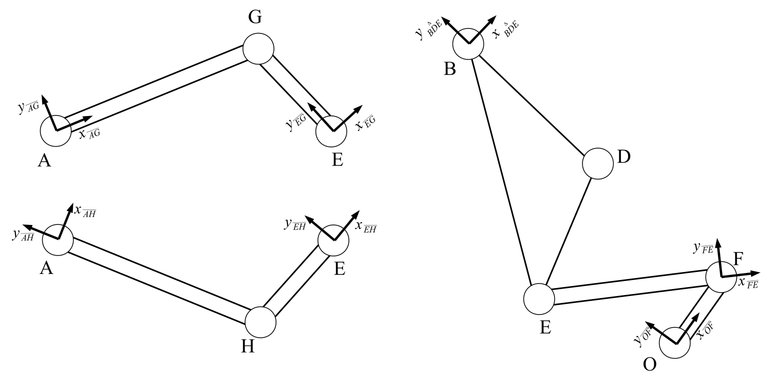
Andrew's squeezer mechanism *[Sch97]* is a planar system composed of seven bodies interconnected through revolution joints, and driven by a motor located in O. The next figure presents the sketch of the mechanism.



The following table reports the system configuration.

System Properties and Configuration	
Spring coefficient	4530 N/m
Spring rest length	0.07785 m
Motor torque	0.033 Nm
β_0	-0.0620 rad

Detailed information about the mechanical structure of each body is reported in next tables, referred to the reference systems presented in the next figure.



Rod Elements Properties					
	Center of Mass (CoM)		Mass	Inertia (CoM)	Length
	X [m]	Y [m]	[Kg]	[Kg m^2]	[m]
OF	0.00092	0.0	0.04325	2.194e-6	0.007
FE	-0.0115	0.0	0.00365	4.410e-7	0.028
EG	0.0	0.01421	0.00706	5.667e-7	0.02
AG	0.02308	0.00916	0.0705	1.169e-5	0.04
AH	-0.00449	-0.01228	0.05498	1.912e-5	0.04
HE	-0.01421	0.0	0.00706	5.667e-7	0.02

Triangular Element Properties, points defined in $X_{BDE} - Y_{BDE}$ SoR		
Center of Mass (CoM) Coordinates	0.01043 m (X)	-0.0187 m (Y)
Mass	0.02372 Kg	
Inertia (CoM)	5.255e-6 Kg m^2	
Point B Coordinates	0 m (X)	0 m (Y)
Point D Coordinates	0.02 m (X)	-0.018 m (Y)
Point E Coordinates	0 m (X)	-0.035 m (Y)

Points in ground X-Y SoR		
Point	X [m]	Y [m]
O	0.0	0.0
A	-0.06934	-0.00227
B	0.03635	0.03273
C	0.014	0.072

Initial Joints Position	
Angle	Value [rad]
β	-0.0620
$O\hat{F}E$	0.0
$F\hat{E}B$	2.088
$F\hat{E}G$	2.341
$E\hat{G}A$	1.792
$E\hat{H}A$	1.348

3.3 Results

The dynamic simulation of the **A03** benchmark was executed for 0.05 s. The starting position of the simulation is defined by the values reported in the last table.

The objective of the simulation is to measure the sytem total energy balance running the simulation in the minimum CPU time. The energy provided to the system by the driving torque is given by:

$$E - E_0 = \tau(\beta - \beta_0)$$

where the pedix 0 indicate the initial condition and E is the mechanical energy of the system.

According to this formulation, the total energy balance can be written as:

$$\Delta U = T + V - E_0 - \tau(\beta - \beta_0)$$

where T is the kinetic energy and V the potential energy.

Since no dissipation is present in the mechanism theoretical value for ΔU is zero.

A second evaluation has been conducted measuring F point displacements and comparing them with the reference solution. The simulation with OpenSim perfectly match the reference values as shown in the next figure.

3.3.1 Computational Performances

To compute the simulation the developed implementation required 0.384 seconds.

Results obtained using an Intel Core i5-4570 @ 3.2 GHz computer running Windows 8.1 64-bit. OpenSim official release used: 3.2.

Comparision with other dynamic engines has been conducted submitting the obtained results to the benchmark collaborative library. Click here[1] gto see the comparison results.

3.4 Videos

Video of the problem simulated in OpenSim is available at https://youtu.be/XOgsQz5iabs

3.5 Download

- Andrew's squeezing mechanism on MBS Benchmark library available at: http://goo.gl/cU4fPg
- OpenSim implementation available at: http://goo.gl/R9tl3z

[1] http://goo.gl/cU4fPg

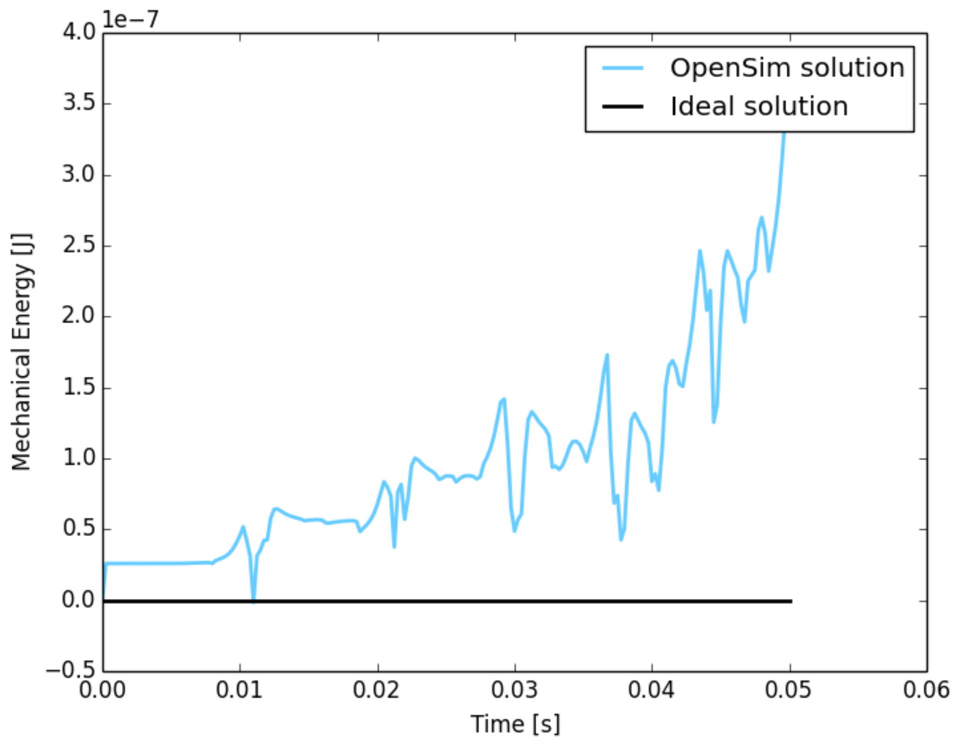


Fig. 3.1: Total energy variation during simulation period from the initial condition. Theoretical variation (black line) and simulated one (blue line).

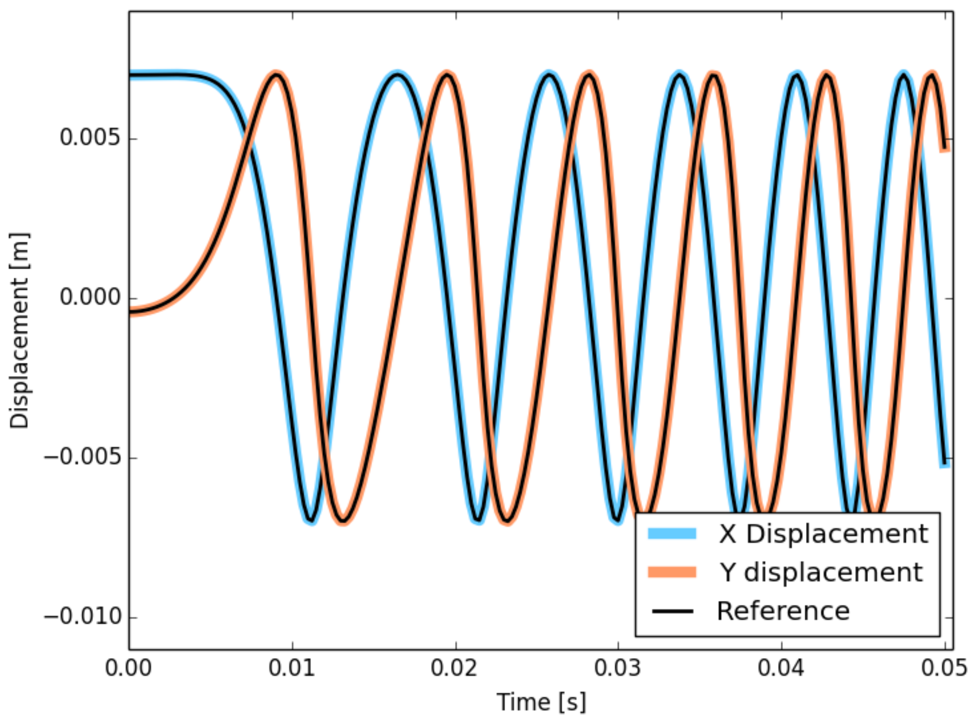


Fig. 3.2: Comparison of the point F displacement between Andrew's mechanism model simulated in OpenSim (colored lines) and MBS benchmark reference values (black dashed lines).

- Videos of Andrew's squeezing mechanism simulated in OpenSim available at: https://youtu.be/XOgsQz5iabs

CHAPTER

FOUR

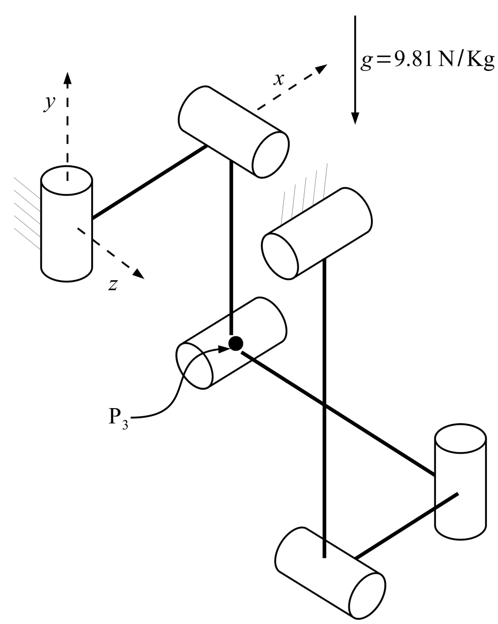
MBS BENCHMARK A04: BRICARD'S MECHANISM

4.1 Benchmark Objective

Bricard's mechanism (benchmark problem **A04**) *[Bri97]* is an example of over-constrained system. Grübler's formula *[Grubler84]* results in no degrees of freedom, however, the particular orientation of the revolute pairs results in a system with one degree of freedom.

4.2 Benchmark Description

The system is composed of five rods with square cross section and six revolute joints. Gravity is acting towards the negative y direction.



The following table reports system properties.

System Properties and Configuration	
Rod length	1.0 m
Rod mass	1.0 Kg
Square cross section length	0.1 m

4.3 Results

The dynamic simulation of the **A04** benchmark was executed for 10 s. The previous figure shows the Bricard's Mechanism in its initial position.

Simulation evaluation has been conducted taking into account the total mechanical energy variation from the initial condition. Total mechanical energy defined as the sum of the kinetic and potential energy of the mechanism. Since no friction or dissipative elements are present in the mechanism energy should be conserved therefore theoretical value for the mechanical energy variation is zero.

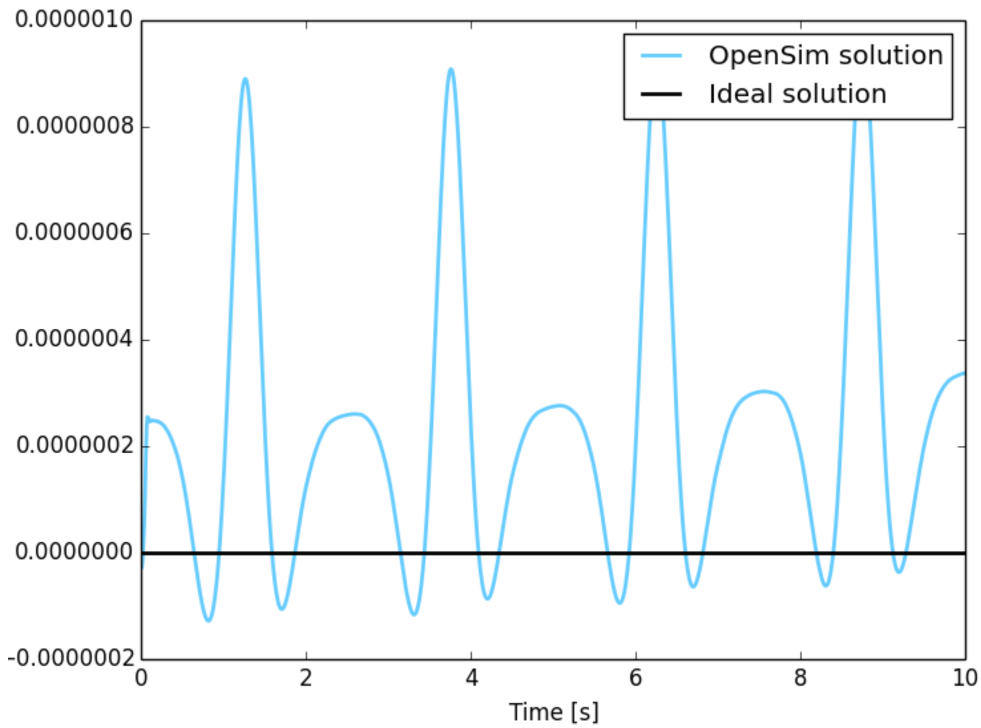


Fig. 4.1: Mechanical energy variation during simulation period from the initial condition. Theoretical variation (black line) and simulated one (blue line).

Next figure shows instead P_3 point displacements estimated with the OpenSim simulation compared with the values provided as reference *[GDLC06]*.

4.3.1 Computational Performances

To compute the simulation the developed implementation required 0.258 seconds.

Results obtained using an Intel Core i5-4570 @ 3.2 GHz computer running Windows 8.1 64-bit. OpenSim official release used: 3.2.

Comparision with other dynamic engines has been conducted submitting the obtained results to the benchmark collaborative library. Click here[1] to see the comparison results.

[1] http://goo.gl/9XLSME

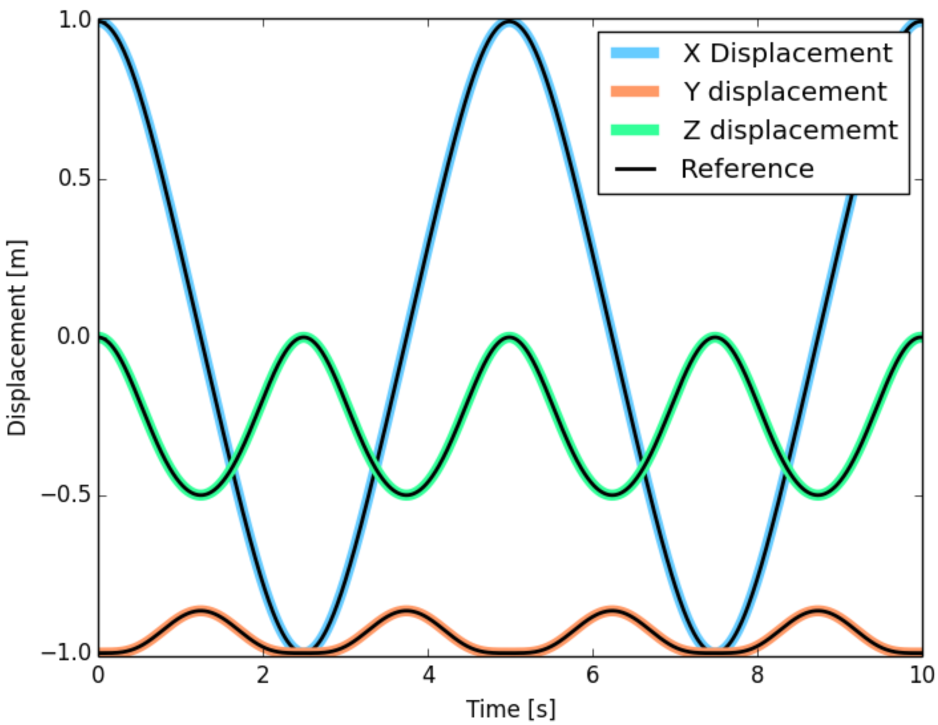


Fig. 4.2: Comparison of the point P_3 displacement between Andrew's mechanism model simulated in OpenSim (colored lines) and MBS benchmark reference values (black dashed lines).

4.4 Videos

Video of the problem simulated in OpenSim is available at https://youtu.be/vBpZ6P5VigA

4.5 Download

- Bricard's mechanism on MBS Benchmark library available at: http://goo.gl/9XLSME
- OpenSim implementation available at: http://goo.gl/R9tl3z
- Video of Bricard's mechanism sumulated in OpenSim available at: https://youtu.be/vBpZ6P5VigA

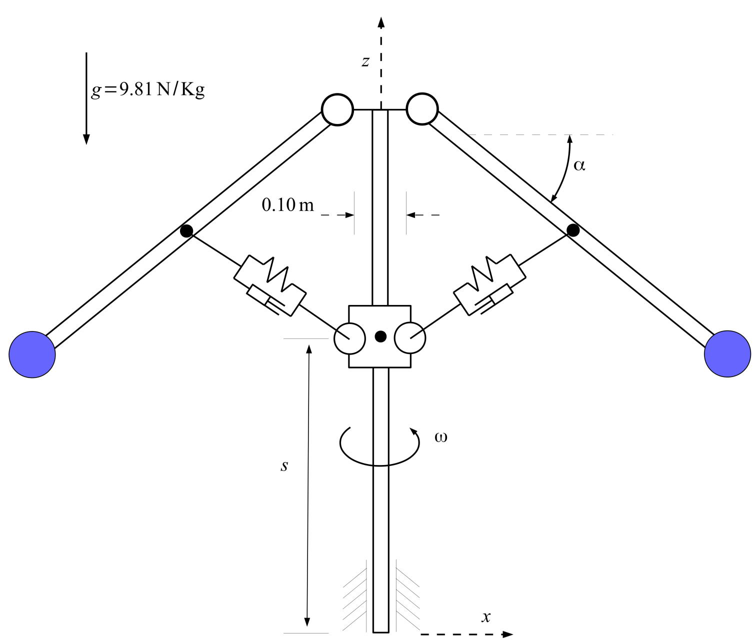
MBS BENCHMARK A05: STIFF FLYBALL GOVERNOR

5.1 Benchmark Objective

The **A05** MBS benchmark problem is an example of a stiff mechanical system.

5.2 Benchmark Description

The **A05** benchmark problem is also known as stiff flyball governor and was invented by J. Watt in the 18th century. In this stiff mechanical system, coupler rods are substituted by spring-damper elements.



Shaft, rods and slider can be modeled as prismatic bodies with the characteristics provided in the next table. Two 5 kilograms point mass are placed on points colored in purple in the previous figure.

System Properties and Configuration	
Shaft, Rods dimensions	$1.0 \times 0.01 \times 0.01m$
Slider dimensions	$0.1 \times 0.1 \times 0.1m$
Density ρ	$3000kg/m^3$
Point masses	5 kg
Spring stiffness K	8e5 N/m
Spring damping C	4e4 Ns/m
Spring rest length	0.5 m
:s	0.5 m
:α	30 degree
:$\dot{\omega}$	$2\pi rad/s$

5.3 Results

The dynamic simulation of the **A05** benchmark was executed for 10 s. The starting position of the system in shown in the previous figure and numerical values are reported in the previous table.

s values estimated with the OpenSim simulation are compared with the values provided as reference *[GDLC06]*.

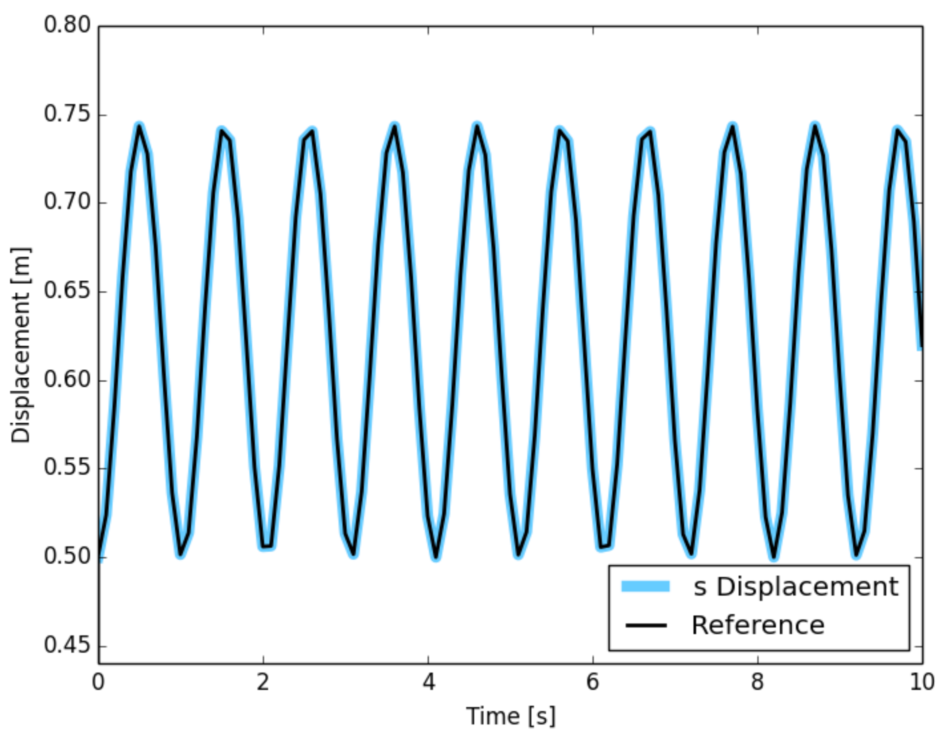


Fig. 5.1: Comparison between OpenSim simulation results for coordinate s (colored line) and MBS benchmark reference value (black dashed line).

5.3.1 Computational Performances

To compute the simulation the developed implementation required 0.233 seconds.

Results obtained using an Intel Core i5-4570 @ 3.2 GHz computer running Windows 8.1 64-bit. OpenSim official release used: 3.2.

Comparision with other dynamic engines has been conducted submitting the obtained results to the benchmark collaborative library. Click here[1] to see the comparison results.

5.4 Videos

Video of the problem simulated in OpenSim is available at https://youtu.be/pNLlsh6tIQU

5.5 Download

- Stiff flyball governor on MBS Benchmark library available at: http://goo.gl/ylkXzN
- OpenSim implementation available at: http://goo.gl/R9tl3z
- Video of stiff flyball governor simulated in OpenSim available at: https://youtu.be/pNLlsh6tIQU

[1] http://goo.gl/ylkXzN

Part IV

Acknowledgements

MBS Benchmarks in Opensim have been developed by the Rehabilitation Engineering Group[2], Dipartimento di Tecnica e Gestione dei Sistemi Industriali[3], Universita' degli Studi di Padova[4].

Luca Tagliapietra, Michele Vivian, Monica Reggiani, and Elena Ceseracciu acknowledge the financial support of the ICT programme within the Seventh Framework Programme for Research of the European Commission (BioMot[5] project, grant number: 611695). [6]

[2] http://reg.gest.unipd.it
[3] http://www.gest.unipd.it
[4] http://www.unipd.it
[5] http://www.biomotproject.eu/
[6] http://www.biomotproject.eu/

[BA94] E. Bayo and A. Avello. Singularity-free augmented lagrangian algorithms for constrained multibody dynamics. *Nonlinear Dynamics*, 5(2):209–231, 1994.

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[DAA+07] S.L. Delp, F.C. Anderson, A.S. Arnold, P. Loan, A. Habib, C.T. John, E. Guendelman, and D.G. Thelen. Opensim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans. on Biomed. Eng.*, 54(11):1940–1950, 2007.

[GDLC06] M. González, D. Dopico, U. Lugrís, and J. Cuadrado. A benchmarking system for mbs simulation software: problem standardization and performance measurement. *Multibody System Dynamics*, 16(2):179–190, 2006.

[Grubler84] M. Grübler, editor. *Oxford Handbook of Innovation*. Ed. Simion, Oxford, 1884.

[Sch97] W. Schiehlen. Multibody system dynamics: roots and perspectives. *Multibody System Dynamics*, 1(2):149–188, 1997.