



# Autonomous Vehicle Simulation (AVS) Laboratory, University of Colorado

## Basilisk Technical Memorandum Document ID: Basilisk-hingedRigidBodyStateEffector HINGED RIGID BODY DYNAMICS MODEL

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<b>Status:</b> In Review
<b>Scope/Contents</b>
<p>The hinged rigid body class is an instantiation of the state effector abstract class. The integrated test is validating the interaction between the hinged rigid body module and the rigid body hub that it is attached to. In this case, a hinged rigid body has a diagonal inertia tensor and is attached to the hub by a single degree of freedom torsional hinged with a linear spring constant and linear damping term. The integrated tests has six scenarios it is testing. The first three are: one with gravity and no damping, one without gravity and without damping, and one without gravity with damping. These first three tests are verifying energy and momentum conservation. In the first two cases orbital energy, orbital momentum, rotational energy, and rotational angular momentum should all be conserved. In the third case only orbital momentum, orbital energy, and rotational momentum should be conserved. This integrated test validates for all three scenarios that all of these parameters are conserved. The fourth scenario is verifying that the steady state deflection while a constant force is being applied matches the back of the envelope (BOE) calculation. The fifth scenario applies a constant force and removes the force and the test verifies that the frequency and amplitude match the BOE calculations. And the sixth scenario verifies that Basilisk gives identical results to a planar Lagrangian dynamical system created independently.</p>

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## Contents

<b>1</b>	<b>Model Description</b>	<b>1</b>
1.1	Introduction . . . . .	1
1.2	Equations of Motion . . . . .	2
1.3	Back Substitution Method . . . . .	2
<b>2</b>	<b>Model Functions</b>	<b>4</b>
<b>3</b>	<b>Model Assumptions and Limitations</b>	<b>4</b>
<b>4</b>	<b>Test Description and Success Criteria</b>	<b>4</b>
4.1	Gravity and no damping scenario . . . . .	5
4.2	No gravity and no damping scenario . . . . .	5
4.3	No gravity with damping scenario . . . . .	5
4.4	Steady State Deflection Verification Scenario . . . . .	5
4.5	Frequency and Amplitude Verification Scenario . . . . .	7
4.6	Lagrangian vs Basilisk Scenario . . . . .	8
<b>5</b>	<b>Test Parameters</b>	<b>8</b>
<b>6</b>	<b>Test Results</b>	<b>10</b>
6.1	Gravity with no damping scenario . . . . .	10
6.2	No Gravity with no damping scenario . . . . .	12
6.3	No Gravity with damping scenario . . . . .	15
6.4	Steady State Deflection Scenario . . . . .	17
6.5	Frequency and Amplitude Verification Scenario . . . . .	18
6.6	Lagrangian vs Basilisk Scenario . . . . .	18
<b>7</b>	<b>User Guide</b>	<b>21</b>

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## 1 Model Description

### 1.1 Introduction

The hinged rigid body class is an instantiation of the state effector abstract class. The state effector abstract class is a base class for modules that have dynamic states or degrees of freedom with respect to the rigid body hub. Examples of these would be reaction wheels, variable speed control moment gyroscopes, fuel slosh particles, etc. Since the state effectors are attached to the hub, the state effectors are directly affecting the hub as well as the hub is back affecting the state effectors.

Specifically, a hinged rigid body state effector is a rigid body that has a diagonal inertia with respect to its  $S_i$  frame as seen in Figure 1. It is attached to the hub through a hinge with a linear torsional spring and linear damping term. The dynamics of this multi-body problem have been derived and can be seen in Reference [1]. The derivation is general for  $N$  number of panels attached to the hub but does not allow for multiple interconnected panels.



into the translational EOM and rearranged:

$$\begin{aligned} & \left( m_{sc}[I_{3 \times 3}] + \sum_{i=1}^N m_{sp_i} d_i \hat{\mathbf{s}}_{i,3} \mathbf{a}_{\theta_i}^T \right) \ddot{\mathbf{r}}_{B/N} + \left( -m_{sc}[\tilde{\mathbf{c}}] + \sum_{i=1}^N m_{sp_i} d_i \hat{\mathbf{s}}_{i,3} \mathbf{b}_{\theta_i}^T \right) \dot{\boldsymbol{\omega}}_{B/N} \\ & = m_{sc} \ddot{\mathbf{r}}_{C/N} - 2m_{sc}[\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{c}' - m_{sc}[\tilde{\boldsymbol{\omega}}_{B/N}][\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{c} - \sum_{i=1}^N \left( m_{sp_i} d_i \dot{\theta}_i^2 \hat{\mathbf{s}}_{i,1} + m_{sp_i} d_i c_{\theta_i} \hat{\mathbf{s}}_{i,3} \right) \end{aligned} \quad (4)$$

Following the same pattern for the hub rotational EOM, Eq. (2), yields:

$$\begin{aligned} & \left[ m_{sc}[\tilde{\mathbf{c}}] + \sum_{i=1}^N \left( I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3} \right) \mathbf{a}_{\theta_i}^T \right] \ddot{\mathbf{r}}_{B/N} \\ & + \left[ [I_{sc,B}] + \sum_{i=1}^N \left( I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3} \right) \mathbf{b}_{\theta_i}^T \right] \dot{\boldsymbol{\omega}}_{B/N} = -[\tilde{\boldsymbol{\omega}}_{B/N}][I_{sc,B}] \boldsymbol{\omega}_{B/N} - [I'_{sc,B}] \boldsymbol{\omega}_{B/N} \\ & - \sum_{i=1}^N \left\{ \left( \dot{\theta}_i [\tilde{\boldsymbol{\omega}}_{B/N}] + c_{\theta_i} [I_{3 \times 3}] \right) \left( I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3} \right) + m_{sp_i} d_i \dot{\theta}_i^2 [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,1} \right\} + \mathbf{L}_B \end{aligned} \quad (5)$$

With the following definitions:

$$\mathbf{a}_{\theta_i} = -\frac{m_{sp_i} d_i}{(I_{s_{i,2}} + m_{sp_i} d_i^2)} \hat{\mathbf{s}}_{i,3} \quad (6a)$$

$$\mathbf{b}_{\theta_i} = -\frac{1}{(I_{s_{i,2}} + m_{sp_i} d_i^2)} \left[ (I_{s_{i,2}} + m_{sp_i} d_i^2) \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{H_i/B}] \hat{\mathbf{s}}_{i,3} \right] \quad (6b)$$

$$\begin{aligned} c_{\theta_i} = \frac{1}{(I_{s_{i,2}} + m_{sp_i} d_i^2)} & \left( -k_i \theta_i - c_i \dot{\theta}_i + \hat{\mathbf{s}}_{i,2} \cdot \boldsymbol{\tau}_{\text{ext}, H_i} + (I_{s_{i,3}} - I_{s_{i,1}} + m_{sp_i} d_i^2) \omega_{s_{i,3}} \omega_{s_{i,1}} \right. \\ & \left. - m_{sp_i} d_i \hat{\mathbf{s}}_{i,3}^T [\tilde{\boldsymbol{\omega}}_{B/N}] [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{r}_{H_i/B} \right) \end{aligned} \quad (6c)$$

The equations can now be organized into the following matrix representation:

$$\begin{bmatrix} [A] & [B] \\ [C] & [D] \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{r}}_{B/N} \\ \dot{\boldsymbol{\omega}}_{B/N} \end{bmatrix} = \begin{bmatrix} \mathbf{v}_{\text{trans}} \\ \mathbf{v}_{\text{rot}} \end{bmatrix} \quad (7)$$

Finally, the hinged rigid body model must make “contributions” to the matrices defined in Equations (7). These contributions are defined in the following equations:

$$[A_{\text{contr}}] = m_{sp_i} d_i \hat{\mathbf{s}}_{i,3} \mathbf{a}_{\theta_i}^T \quad (8)$$

$$[B_{\text{contr}}] = m_{sp_i} d_i \hat{\mathbf{s}}_{i,3} \mathbf{b}_{\theta_i}^T \quad (9)$$

$$[C_{\text{contr}}] = (I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3}) \mathbf{a}_{\theta_i}^T \quad (10)$$

$$[D_{\text{contr}}] = (I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3}) \mathbf{b}_{\theta_i}^T \quad (11)$$

$$\mathbf{v}_{\text{trans,contr}} = -\left( m_{sp_i} d_i \dot{\theta}_i^2 \hat{\mathbf{s}}_{i,1} + m_{sp_i} d_i c_{\theta_i} \hat{\mathbf{s}}_{i,3} \right) \quad (12)$$

$$\mathbf{v}_{\text{rot,contr}} = -\left\{ \left( \dot{\theta}_i [\tilde{\boldsymbol{\omega}}_{B/N}] + c_{\theta_i} [I_{3 \times 3}] \right) \left( I_{s_{i,2}} \hat{\mathbf{s}}_{i,2} + m_{sp_i} d_i [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,3} \right) + m_{sp_i} d_i \dot{\theta}_i^2 [\tilde{\mathbf{r}}_{S_{c,i}/B}] \hat{\mathbf{s}}_{i,1} \right\} \quad (13)$$

The final equation that is needed is:

$$\ddot{\theta}_i = \mathbf{a}_{\theta_i}^T \ddot{\mathbf{r}}_{B/N} + \mathbf{b}_{\theta_i}^T \dot{\boldsymbol{\omega}}_{B/N} + c_{\theta_i} \quad (14)$$

## 2 Model Functions

This module is intended to be used as an approximation to a flexing body attached to the spacecraft. Examples include solar arrays, antennas, and other appended bodies that would exhibit flexing behavior. Below is a list of functions that this model performs:

- Compute its contributions to the mass properties of the spacecraft
- Provides matrix contributions for the back substitution method
- Compute its derivatives for  $\theta$  and  $\dot{\theta}$
- Adds energy and momentum contributions to the spacecraft

## 3 Model Assumptions and Limitations

Below is a summary of the assumptions/limitations:

- Is a first-order approximation to a flexing body
- Is developed in such a way that does not require constraints to be met
- The hinged rigid body must have a diagonal inertia tensor with respect to the  $\mathcal{S}_i$  frame as seen in Figure 1
- Only linear spring and damping terms
- Will only approximate one flexing mode at a time
- Cannot simulate multiple interconnected panels
- The hinged rigid body will always stay attached to the hub (the hinge does not have torque limits)
- The hinge does not have travel limits, therefore if the spring is not stiff enough it will unrealistically travel through bounds such as running into the spacecraft hub
- The EOMs are nonlinear equations of motion, therefore there can be inaccuracies (and divergence) that result from integration. Having a time step of  $\leq 0.10$  sec is recommended.

## 4 Test Description and Success Criteria

This test is located in `SimCode/dynamics/HingedRigidBodyStates/UnitTest/test_hingedRigidBodyStateEffector.py`. In this integrated test there are two hinged rigid bodies connected to the spacecraft hub. Depending on the scenario, there are different success criteria. These are outlined in the following subsections:

#### 4.1 Gravity and no damping scenario

In this test the simulation is placed into orbit around Earth with point gravity and has no damping in the hinged rigid bodies. The following parameters are being tested.

- Conservation of orbital angular momentum
- Conservation of orbital energy
- Conservation of rotational angular momentum
- Conservation of rotational energy
- Achieving the expected final attitude

#### 4.2 No gravity and no damping scenario

In this test, the spacecraft is placed in free space (no gravity) and has no damping in the hinged rigid bodies. The following parameters describe the success criteria.

- Conservation of orbital angular momentum
- Conservation of orbital energy
- Conservation of rotational angular momentum
- Conservation of rotational energy
- Achieving the expected final attitude (same final attitude as the Gravity with no damping scenario)
- Achieving the expected final position
- Conservation of velocity of center of mass

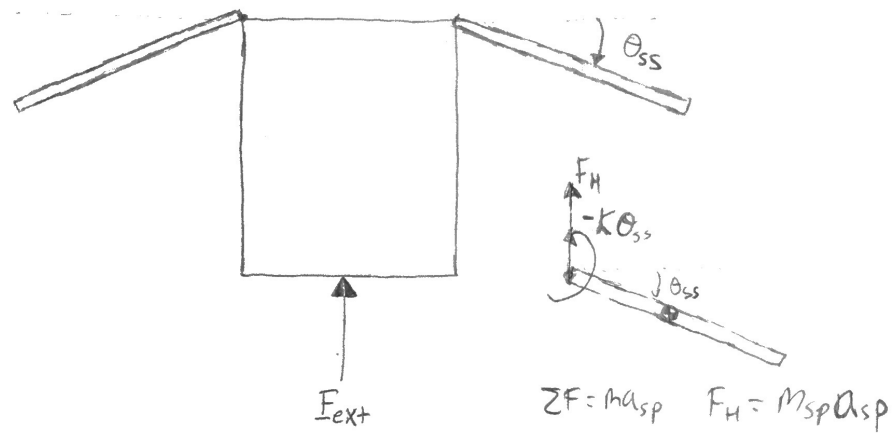
#### 4.3 No gravity with damping scenario

In this test, the spacecraft is placed in free space (no gravity) and has damping in the hinged rigid bodies. The following parameters describe the success criteria.

- Conservation of orbital angular momentum
- Conservation of orbital energy
- Conservation of rotational angular momentum
- Conservation of velocity of center of mass

#### 4.4 Steady State Deflection Verification Scenario

The BOE calculation for the steady state deflection can be seen in Fig. 2. As it can be seen the resulting steady state deflection does not have a closed form solution so a root solving function must be used to converge on the solution. A Newton-Raphson method was chosen and the success criteria for this test is whether Basilisk gives the same results as this BOE calculation within a certain tolerance. The spacecraft has a constant force applied through the whole simulation with the hinged rigid bodies initially undeflected and they have damping. The force is always applied through the center of mass of the spacecraft and results in no rotation of the spacecraft.



At steady state, we know that  
 $\sum \tau_H = 0$  because  $\ddot{\theta} = 0$ . Therefore,

$$\sum \tau_{com} = -k\theta_{ss} - m_{sp} a_{sp} (d \cos \theta_{ss}) = I \ddot{\theta}$$

$$a_{sp} = \frac{F}{m_{sc}}$$

$$-k\theta_{ss} = m_{sp} \left( \frac{F}{m_{sc}} \right) d \cos \theta_{ss}$$

$$f(\theta) = k\theta_{ss} + m_{sp} a_{sp} (d \cos \theta_{ss})$$

**Fig. 2:** Steady State Deflection BOE Calculation



## 4.5 Frequency and Amplitude Verification Scenario

The BOE calculation for the frequency of oscillation of flexing hinged rigid bodies when a constant force is being applied to the spacecraft is done by making simplifications to the flexing equation seen in the Model Description Section. The following assumptions are made to simplify the equations:

1. The force is being directed through the center of mass of the spacecraft, along the  $\hat{\mathbf{b}}_2$  direction
2. The panels are initially undeflected and they are symmetric therefore the body will not rotate
3. Rotation is no longer apart of the equations so the translation and solar panel equations are the only equations needed
4.  $\hat{\mathbf{s}}_{i,3}$  is assumed to be equal to  $\hat{\mathbf{h}}_{i,3}$  in the equations of motion
5. No external torque is being applied directly to the hinged rigid bodies
6. Non-linear terms are neglected

Using the third assumption from above, the rotational motion is taken out of the equations of motion:

$$m_{sc}\ddot{\mathbf{r}}_{B/N} + \sum_i^N m_{sp_i} d_i \hat{\mathbf{s}}_{i,3} \ddot{\theta}_i = \mathbf{F}_{ext} - \sum_i^N m_{sp_i} d_i \dot{\theta}_i^2 \hat{\mathbf{s}}_{i,1} \quad (15)$$

$$m_{sp_i} d_i \hat{\mathbf{s}}_{i,3}^T \ddot{\mathbf{r}}_{B/N} + (I_{s_{i,2}} + m_{sp_i} d_i^2) \ddot{\theta}_i = -k_i \theta_i - c_i \dot{\theta}_i + \hat{\mathbf{s}}_{i,2}^T \boldsymbol{\tau}_{ext, H_i} \quad (16)$$

Next, assumptions 4-6 are applied:

$$m_{sc}\ddot{\mathbf{r}}_{B/N} + \sum_i^N m_{sp_i} d_i \hat{\mathbf{h}}_{i,3} \ddot{\theta}_i = \mathbf{F}_{ext} \quad (17)$$

$$m_{sp_i} d_i \hat{\mathbf{h}}_{i,3}^T \ddot{\mathbf{r}}_{B/N} + (I_{s_{i,2}} + m_{sp_i} d_i^2) \ddot{\theta}_i = -k_i \theta_i - c_i \dot{\theta}_i \quad (18)$$

Finally, knowing that the force is being directed along the  $\hat{\mathbf{b}}_2$  axis and that the spacecraft will not rotate, the equations simplify to:

$$m_{sc}\ddot{y}_{B/N} + \sum_i^N m_{sp_i} d_i \ddot{\theta}_i = F_y \quad (19)$$

$$m_{sp_i} d_i \ddot{y}_{B/N} + (I_{s_{i,2}} + m_{sp_i} d_i^2) \ddot{\theta}_i = -k_i \theta_i - c_i \dot{\theta}_i \quad (20)$$

Converting these equations to state space:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{sc} & 0 & m_{sp_1} d_1 & 0 & m_{sp_2} d_2 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & m_{sp_1} d_1 & 0 & I_{s_{1,2}} + m_{sp_1} d_1^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & m_{sp_2} d_2 & 0 & 0 & 0 & I_{s_{2,2}} + m_{sp_2} d_2^2 \end{bmatrix} \begin{bmatrix} \dot{y}_{B/N} \\ \ddot{y}_{B/N} \\ \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -k_1 & -c_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -k_2 & -c_2 \end{bmatrix} \begin{bmatrix} y_{B/N} \\ \dot{y}_{B/N} \\ \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ F_y \\ 0 \\ 0 \end{bmatrix} \quad (21)$$

Written in a more compact form:

$$[M]\dot{\mathbf{X}} = [A]\mathbf{X} + \mathbf{F} \quad (22)$$

The equivalent dynamics matrix for this coupled system is:

$$[\tilde{A}] = [M][A] \quad (23)$$

Finding the eigenvalues of  $[\tilde{A}]$  will describe the coupled natural frequencies of the combined system. The integrated test for this scenario ensures that the analytical coupled frequency of oscillation matches the frequency obtained from the simulation.

The next BOE calculation that is needed is to find the maximum deflection while the force is being applied and when the force is not being applied (with the assumption that there is no damping). When the force is being applied the following max deflection can be seen in the following equation:

$$\theta_{\max} = 2\theta_{SS} \quad (24)$$

which uses the definition of  $\theta_{SS}$  from Fig. 2.

Finally, the maximum deflection when the force is not being applied uses approximate energy techniques seen in the following equations:

$$E_0 = \frac{1}{2}I_{sp}\dot{\theta}(t_{\text{off}})^2 + \frac{1}{2}m_{sp}\left[d\dot{\theta}(t_{\text{off}})\right]^2 + \frac{1}{2}k\theta(t_{\text{off}})^2 \quad (25)$$

$E_0$  is the energy when force is turned off and time:  $t_{\text{off}}$ . Next the max deflection can be approximated by using the following equation:

$$\theta_{\max} = \sqrt{\frac{2E_0}{k}} \quad (26)$$

Again, just like the frequency BOE calculation, this is an approximation and neglects the energy stored in the spacecraft hub that a portion will be transferred to the oscillations. The test results for both the frequency and this maximum deflection reflects this approximation in the tolerances.

#### 4.6 Lagrangian vs Basilisk Scenario

In this scenario the equations of motion for a planar simulation of a spacecraft hub and two hinged rigid bodies using Lagrangian mechanics was developed using Mathematica. The mathematica script can be seen in the support folder in the following file name: PlanarFlexibleDynamicsDerivation. This simulation is ran independently in the integrated test and the results are compared vs Basilisk results. A force and torque is applied for a certain amount of time, then turned off. Then another pulse of a force and torque is applied and turn off and the simulation runs for another few seconds.

### 5 Test Parameters

Since this is an integrated test, the inputs to the test are the physical parameters of the spacecraft along with the initial conditions of the states. These parameters are outlined in Tables 2- 5. Additionally, the error tolerance used for the relative accuracy checks is 1e-10.

**Table 2:** Spacecraft Hub Parameters

Name	Description	Value	Units
mHub	mass	750.0	kg
IHubPntBc_B	Inertia in $\mathcal{B}$ frame	$\begin{bmatrix} 900.0 & 0.0 & 0.0 \\ 0.0 & 600.0 & 0.0 \\ 0.0 & 0.0 & 600.0 \end{bmatrix}$	kg-m <sup>2</sup>
r_BcB_B	CoM Location in $\mathcal{B}$ frame	$[0.0 \ 0.0 \ 1.0]^T$	m

**Table 3:** Hinged Rigid Body 1 Parameters

Name	Description	Value	Units
mass	mass	100.0	kg
IPntS_S	Inertia in $\mathcal{S}$ frame	$\begin{bmatrix} 100.0 & 0.0 & 0.0 \\ 0.0 & 50.0 & 0.0 \\ 0.0 & 0.0 & 50.0 \end{bmatrix}$	kg-m <sup>2</sup>
d	CoM location	1.5	m
k	Spring Constant	100.0	N-m/rad
c	Damping Term	0.0 (6.0 - damping scenario)	N-m-s/rad
r_HB_B	Hinge Location in $\mathcal{B}$ frame	$[0.5 \ 0.0 \ 1.0]^T$	m
dcm_HB	$\mathcal{B}$ to $\mathcal{H}$ DCM	$\begin{bmatrix} -1.0 & 0.0 & 0.0 \\ 0.0 & -1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$	-

**Table 4:** Hinged Rigid Body 2 Parameters

Name	Description	Value	Units
mass	mass	100.0	kg
IPntS_S	Inertia in $\mathcal{S}$ frame	$\begin{bmatrix} 100.0 & 0.0 & 0.0 \\ 0.0 & 50.0 & 0.0 \\ 0.0 & 0.0 & 50.0 \end{bmatrix}$	kg-m <sup>2</sup>
d	CoM location	1.5	m
k	Spring Constant	100.0	N-m/rad
c	Damping Term	0.0 (7.0 - damping scenario)	N-m-s/rad
r_HB_B	Hinge Location in $\mathcal{B}$ frame	$[-0.5 \ 0.0 \ 1.0]^T$	m
dcm_HB	$\mathcal{B}$ to $\mathcal{H}$ DCM	$\begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$	-

**Table 5:** Initial Conditions for Energy Momentum Conservation Scenarios

Name	Description	Value	Units
(Panel 1) thetaInit	(Panel 1) Initial $\theta$	5.0	deg
(Panel 1) thetaDotInit	(Panel 1) Initial $\dot{\theta}$	0.0	deg
(Panel 2) thetaInit	(Panel 2) Initial $\theta$	0.0	deg
(Panel 2) thetaDotInit	(Panel 2) Initial $\dot{\theta}$	0.0	deg
r_CN_NInit	Initial Position of S/C (gravity scenarios)	$[-4020339 \ 7490567 \ 5248299]^T$	m
v_CN_NInit	Initial Velocity of S/C (gravity scenarios)	$[-5199.78 \ -3436.68 \ 1041.58]^T$	m/s
r_CN_NInit	Initial Position of S/C (no gravity)	$[0.1 \ -0.4 \ 0.3]^T$	m
v_CN_NInit	Initial Velocity of S/C (no gravity)	$[-0.2 \ 0.5 \ 0.1]^T$	m/s
sigma_BNInit	Initial MRP of $\mathcal{B}$ frame	$[0.0 \ 0.0 \ 0.0]^T$	-
omega_BN_BInit	Initial Angular Velocity of $\mathcal{B}$ frame	$[0.1 \ -0.1 \ 0.1]^T$	rad/s

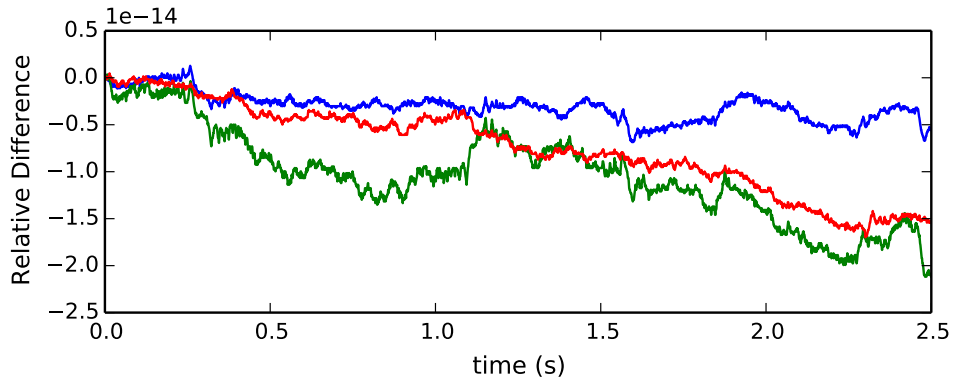
**Table 6:** Error Tolerance

Test	Relative Tolerance
Energy and Momentum Conservation	1e-10
Steady State Deflection	1e-6
Frequency verification	0.12
Max deflection with force on	1e-3
Max deflection with force off	0.12
Lagrangian vs Basilisk comparison	1e-10

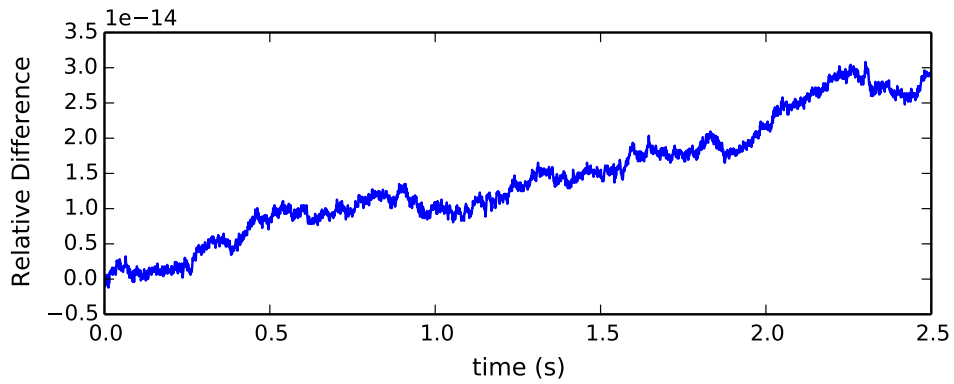
## 6 Test Results

The following figures show the conservation of the quantities described in the success criteria for each scenario. The conservation plots are all relative difference plots. All conservation plots show integration error which is the desired result. In the python test these values are automatically checked therefore when the tests pass, these values have all been confirmed to be conserved.

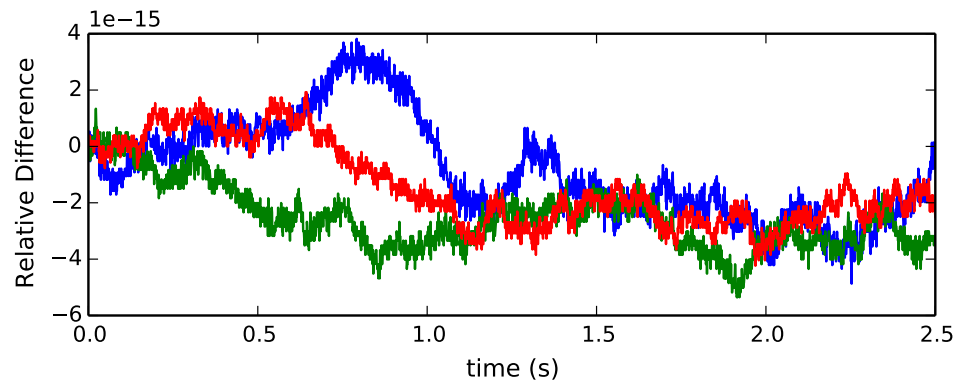
### 6.1 Gravity with no damping scenario



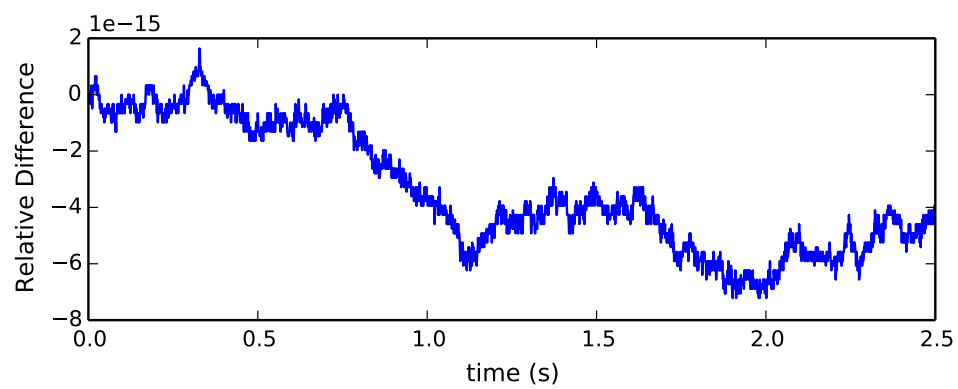
**Fig. 3:** Change in Orbital Angular Momentum with Gravity



**Fig. 4:** Change in Orbital Energy with Gravity

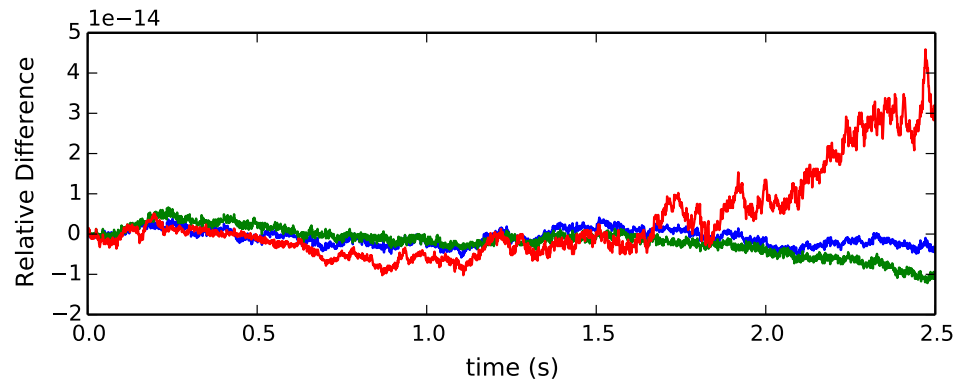


**Fig. 5:** Change In Rotational Angular Momentum with Gravity

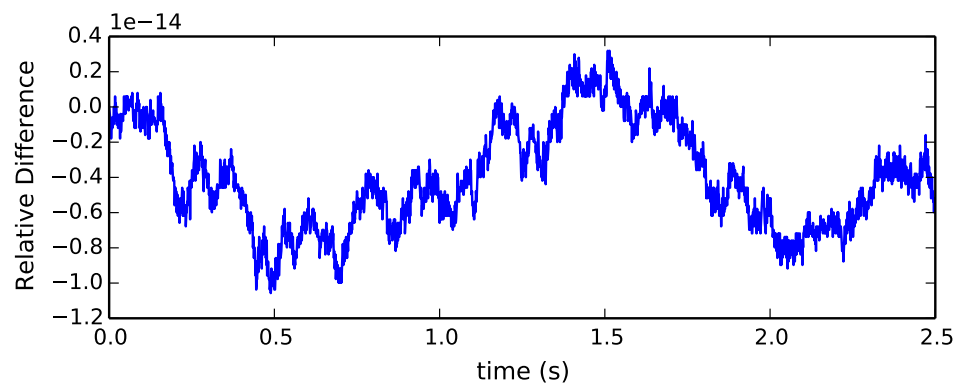


**Fig. 6:** Change In Rotational Energy with Gravity

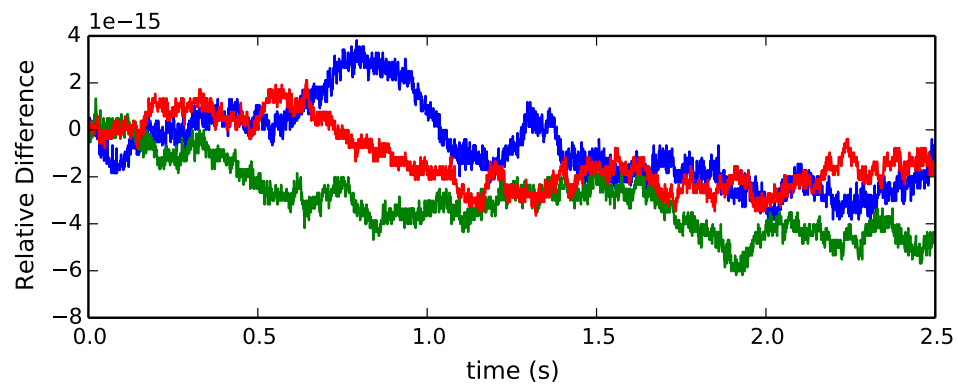
## 6.2 No Gravity with no damping scenario



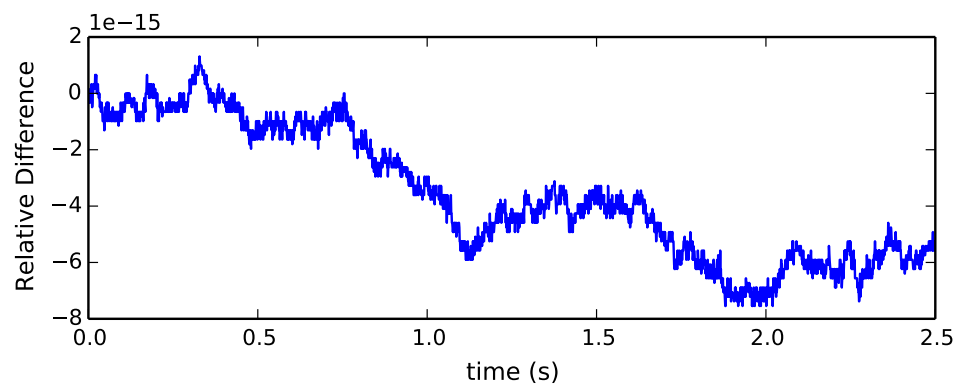
**Fig. 7:** Change in Orbital Angular Momentum No Gravity



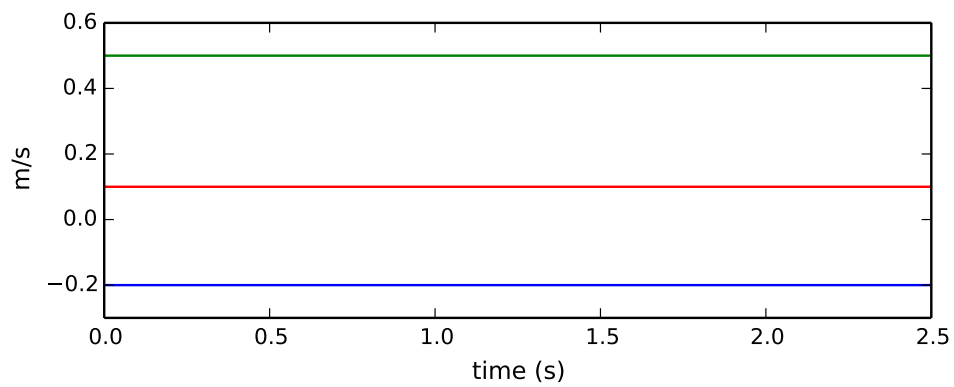
**Fig. 8:** Change in Orbital Energy No Gravity



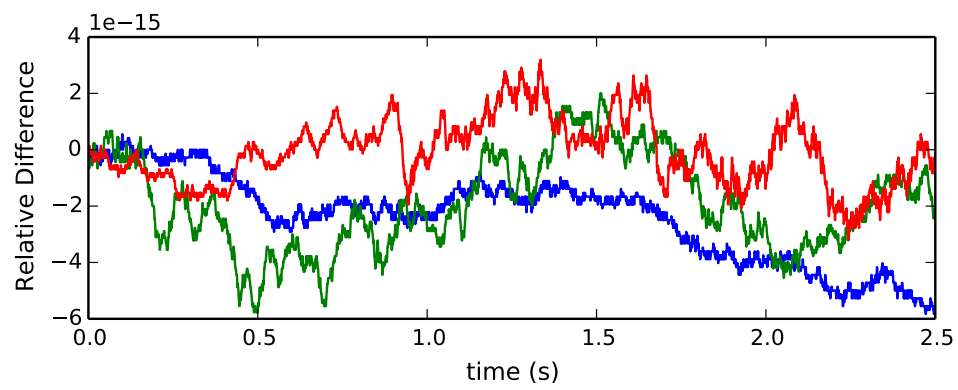
**Fig. 9:** Change In Rotational Angular Momentum No Gravity



**Fig. 10:** Change In Rotational Energy No Gravity



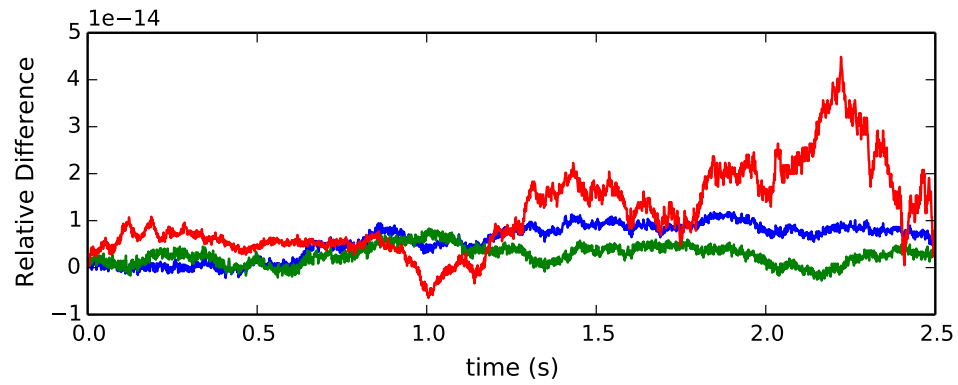
**Fig. 11:** Velocity Of Center Of Mass No Gravity



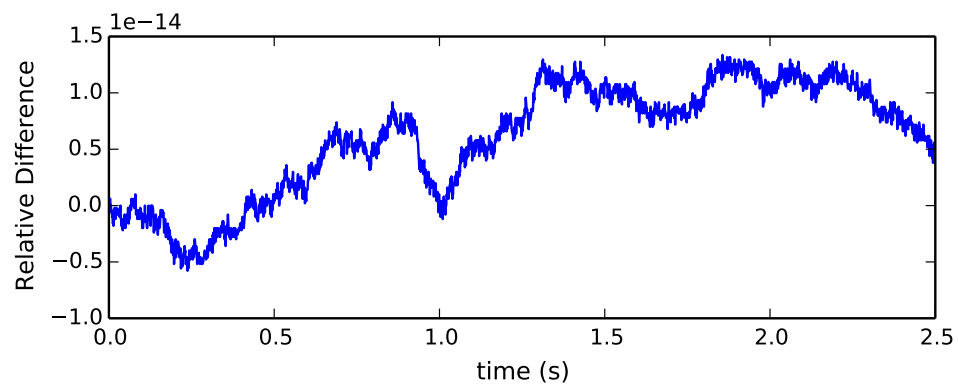
**Fig. 12:** Change In Velocity Of Center Of Mass No Gravity



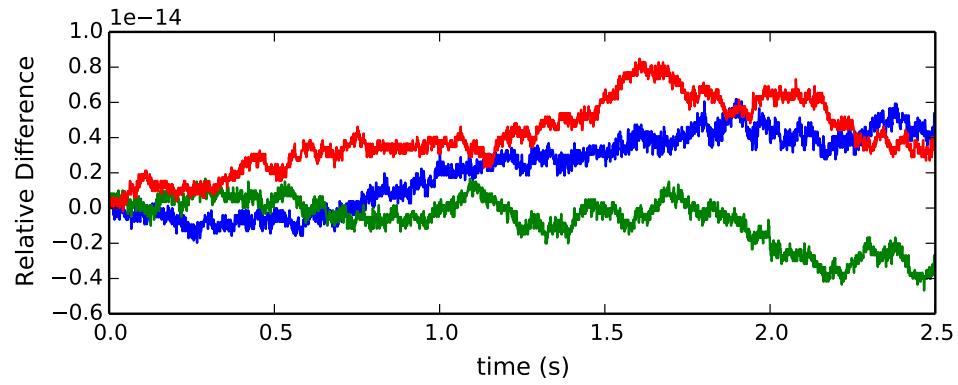
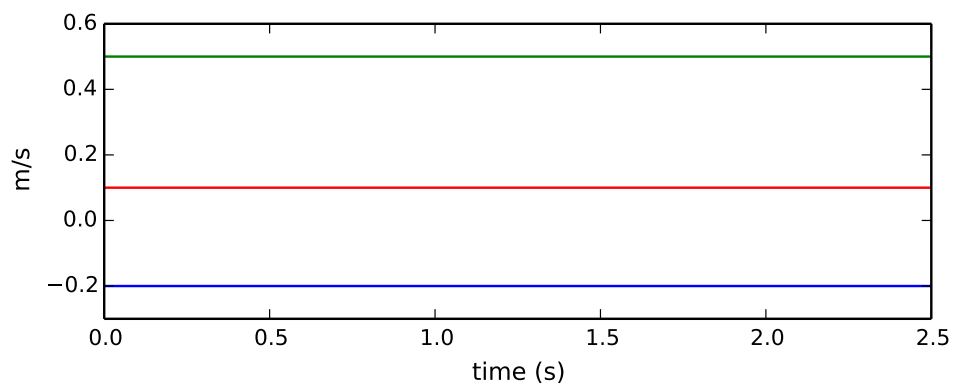
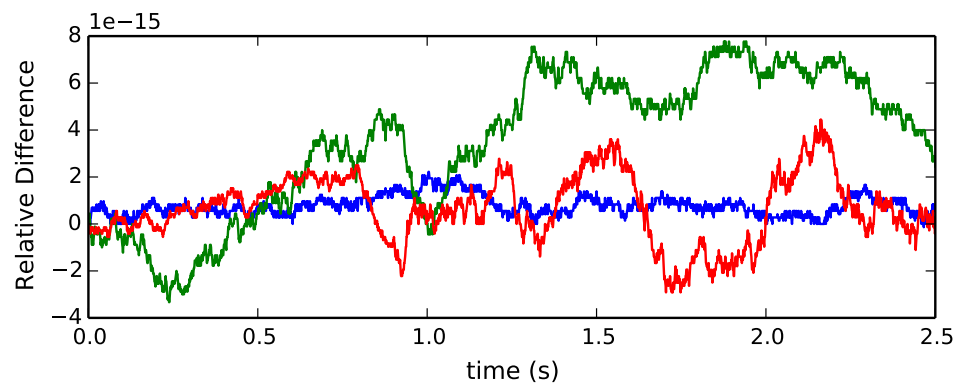
### 6.3 No Gravity with damping scenario



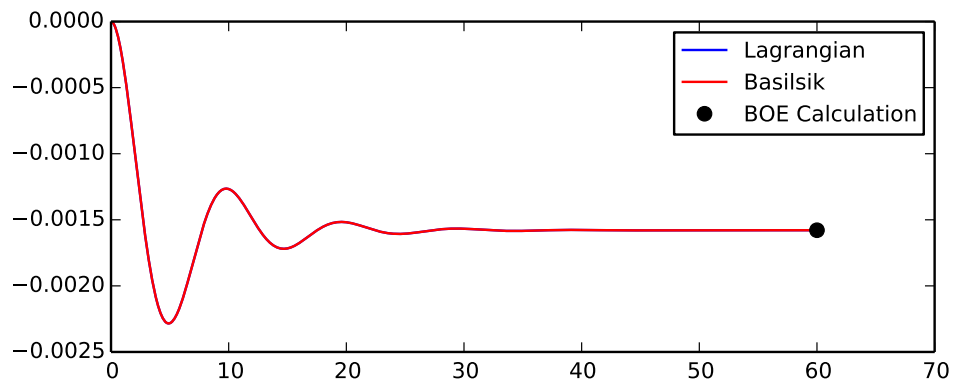
**Fig. 13:** Change in Orbital Angular Momentum No Gravity with Damping



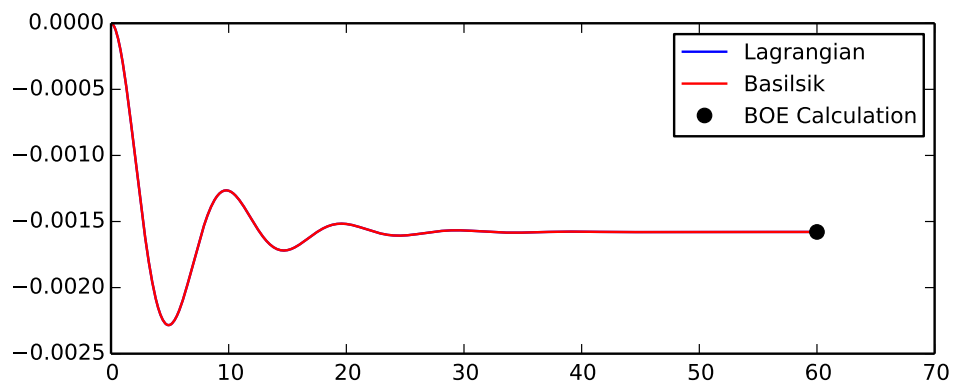
**Fig. 14:** Change in Orbital Energy No Gravity with Damping

**Fig. 15:** Change In Rotational Angular Momentum No Gravity with Damping**Fig. 16:** Velocity Of Center Of Mass No Gravity with Damping**Fig. 17:** Change In Velocity Of Center Of Mass No Gravity with Damping

## 6.4 Steady State Deflection Scenario



**Fig. 18:** BOE Calculation for Steady State Theta 1 Deflection vs Simulation



**Fig. 19:** BOE Calculation for Steady State Theta 2 Deflection vs Simulation

## 6.5 Frequency and Amplitude Verification Scenario

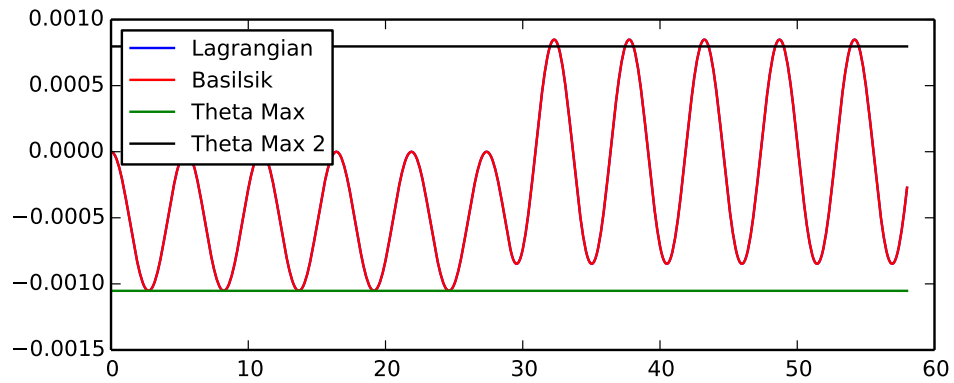


Fig. 20: Max Theta While Forcing

## 6.6 Lagrangian vs Basilisk Scenario

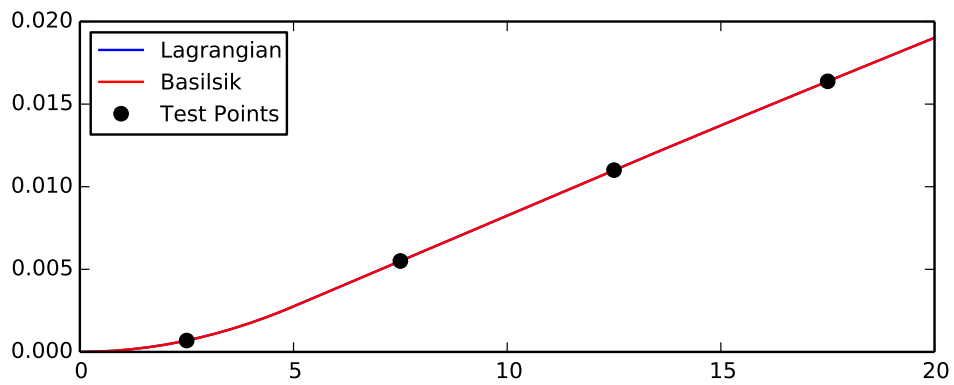


Fig. 21: X Position Lagrangian Vs Basilisk

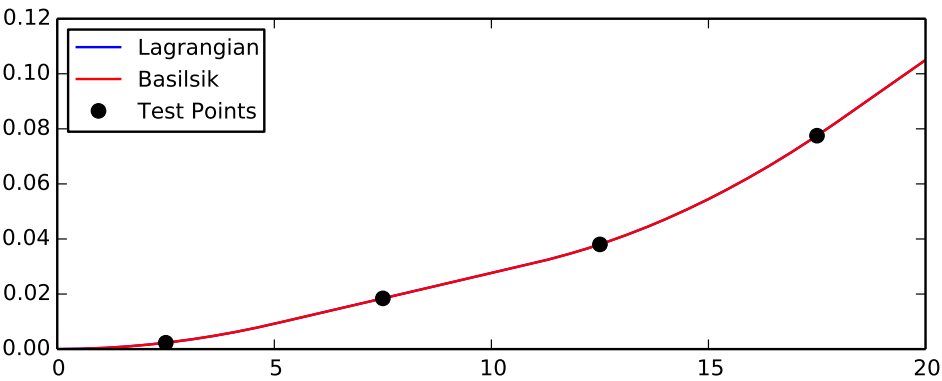


Fig. 22: Y Position Lagrangian Vs Basilisk

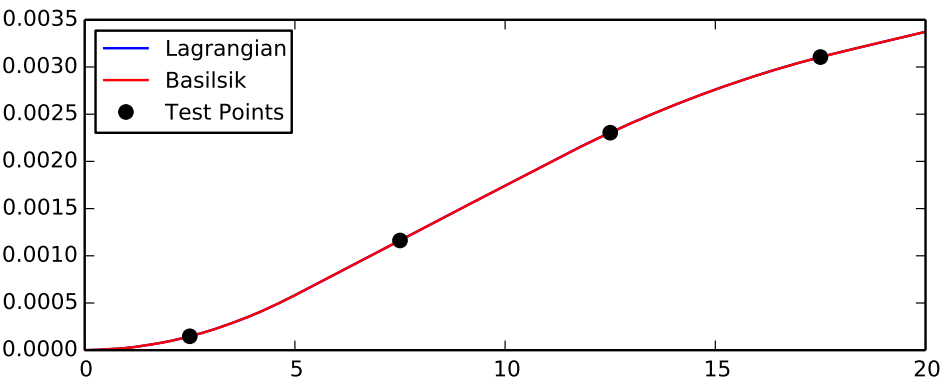


Fig. 23: Theta Lagrangian Vs Basilisk

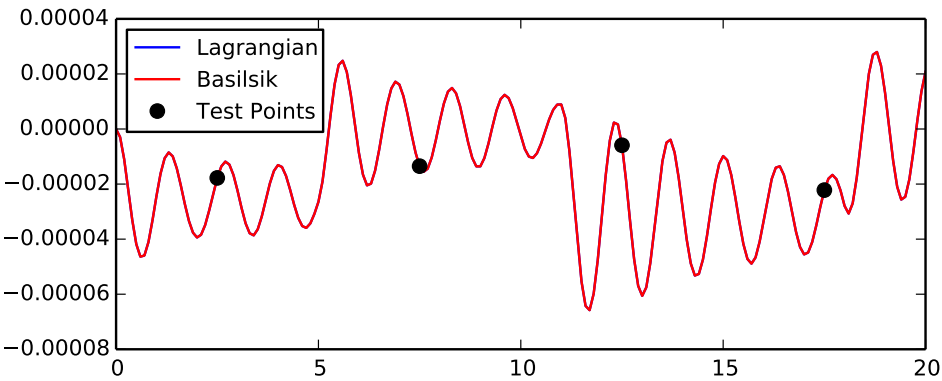
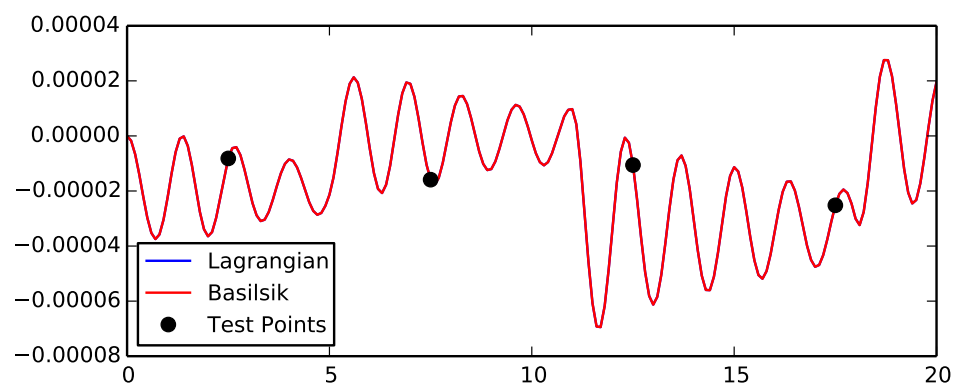


Fig. 24: Theta 1 Position Lagrangian Vs Basilisk



**Fig. 25:** Theta 2 Lagrangian Vs Basilisk

## 7 User Guide

This section is to outline the steps needed to setup a Hinged Rigid Body State Effector in python using Basilisk.

1. Import the `hingedRigidBodyStateEffector` class:  
`import hingedRigidBodyStateEffector`
2. Create an instantiation of a Hinged Rigid body:  
`panel1 = hingedRigidBodyStateEffector.HingedRigidBodyStateEffector()`
3. Define all physical parameters for a Hinged Rigid Body. For example:  
`IPntS.S = [[100.0, 0.0, 0.0], [0.0, 50.0, 0.0], [0.0, 0.0, 50.0]]` Do this for all of the parameters for a Hinged Rigid Body seen in the Hinged Rigid Body 1 Parameters Table.
4. Define the initial conditions of the states:  
`panel1.thetaInit = 5*numpy.pi/180.0    panel1.thetaDotInit = 0.0`
5. Define a unique name for each state:  
`panel1.nameOfThetaState = "hingedRigidBodyTheta1"    panel1.nameOfThetaDotState = "hinged-RigidBodyThetaDot1"`
6. Finally, add the panel to your spacecraftPlus:  
`scObject.addStateEffector(unitTestSim.panel1)`. See spacecraftPlus documentation on how to set up a spacecraftPlus object.

## REFERENCES

- [1] C. Allard, Hanspeter Schaub, and Scott Piggott. General hinged solar panel dynamics approximating first-order spacecraft flexing. In *AAS Guidance and Control Conference*, Breckenridge, CO, Feb. 5–10 2016. Paper No. AAS-16-156.