



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

**Basilisk Technical Memorandum
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LINEAR SPRING MASS DAMPER DYNAMICS MODEL**

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Scope/Contents
<p>The linear spring mass damper class is an instantiation of the state effector abstract class. The integrated test is validating the interaction between the linear spring mass damper module and the rigid body hub that it is attached to. There can be general number of linear spring mass damper particles attached to the spacecraft and can be oriented in any directions with the respect to the rigid body hub. This document outlines the analytical development of the model and describes the efforts completed to validate/verify the model.</p>

Rev	Change Description	By	Date
1.0	Initial Draft	C. Allard	20171221
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1 Model Description

1.1 Derivation of Equations of Motion - Newtonian Mechanics

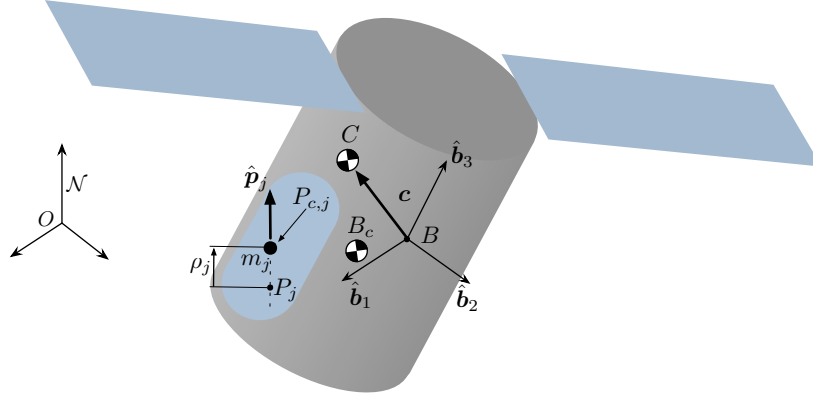


Fig. 1: Frame and variable definitions used for formulation

1.1.1 Rigid Spacecraft Hub Translational Motion

Following a similar derivation as in previous work,¹ the derivation begins with Newton's second law for the center of mass of the spacecraft.

$$\ddot{\mathbf{r}}_{C/N} = \frac{\mathbf{F}}{m_{sc}} \quad (1)$$

Ultimately the acceleration of the body frame or point B is desired

$$\ddot{\mathbf{r}}_{B/N} = \ddot{\mathbf{r}}_{C/N} - \ddot{\mathbf{c}} \quad (2)$$

The definition of \mathbf{c} can be seen in Eq. (3).

$$\mathbf{c} = \frac{1}{m_{sc}} \left(m_{\text{hub}} \mathbf{r}_{B_c/B} + \sum_{j=1}^{N_P} m_j \mathbf{r}_{P_{c,j}/B} \right) \quad (3)$$

To find the inertial time derivative of \mathbf{c} , it is first necessary to find the time derivative of \mathbf{c} with respect to the body frame. A time derivative of any vector, \mathbf{v} , with respect to the body frame is denoted by \mathbf{v}' ; the inertial time derivative is labeled as $\dot{\mathbf{v}}$. The first and second body-relative time derivatives of \mathbf{c} can be seen in Eqs. (7) and (8).

$\mathbf{r}_{P_{c,j}/B}$ is defined in the following

$$\mathbf{r}_{P_{c,j}/B} = \mathbf{r}_{P_j/B} + \rho_j \hat{\mathbf{p}}_j \quad (4)$$

And, the first and second body time derivatives of $\mathbf{r}_{P_{c,j}/B}$ are

$$\mathbf{r}'_{P_{c,j}/B} = \dot{\rho}_j \hat{\mathbf{p}}_j \quad (5)$$

$$\mathbf{r}''_{P_{c,j}/B} = \ddot{\rho}_j \hat{\mathbf{p}}_j \quad (6)$$

\mathbf{c}' and \mathbf{c}'' are defined in the following equations

$$\mathbf{c}' = \frac{1}{m_{sc}} \sum_{j=1}^{N_P} m_j \dot{\rho}_j \hat{\mathbf{p}}_j \quad (7)$$

$$\mathbf{c}'' = \frac{1}{m_{sc}} \sum_{j=1}^{N_P} m_j \ddot{\rho}_j \hat{\mathbf{p}}_j \quad (8)$$

Using the transport theorem² yields the following definition for $\ddot{\mathbf{c}}$

$$\ddot{\mathbf{c}} = \mathbf{c}'' + 2\boldsymbol{\omega}_{B/N} \times \mathbf{c}' + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{c} + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{c}) \quad (9)$$

Eq. (2) is updated to include Eq. (9)

$$\ddot{\mathbf{r}}_{B/N} = \ddot{\mathbf{r}}_{C/N} - \mathbf{c}'' - 2\boldsymbol{\omega}_{B/N} \times \mathbf{c}' - \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{c} - \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{c}) \quad (10)$$

Substituting Eq.(8) into Eq.(10) results in

$$\ddot{\mathbf{r}}_{B/N} = \ddot{\mathbf{r}}_{C/N} - \frac{1}{m_{sc}} \sum_{j=1}^{N_P} m_j \ddot{\rho}_j \hat{\mathbf{p}}_j = -2\boldsymbol{\omega}_{B/N} \times \mathbf{c}' - \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{c} - \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{c}) \quad (11)$$

Moving second order terms to the left hand side and introducing the tilde matrix² to replace the cross product operators simplifies the equation to

$$m_{sc} \ddot{\mathbf{r}}_{B/N} - m_{sc} [\tilde{\mathbf{c}}] \dot{\boldsymbol{\omega}}_{B/N} + \sum_{j=1}^{N_P} m_j \hat{\mathbf{p}}_j \ddot{\rho}_j = \mathbf{F}_{ext} - 2m_{sc} [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{c}' - m_{sc} [\tilde{\boldsymbol{\omega}}_{B/N}] [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{c} \quad (12)$$

Equation (12) is the translational motion equation and is the first EOM needed to describe the motion of the spacecraft. The following section develops the rotational EOM.

1.1.2 Rigid Spacecraft Hub Rotational Motion

Starting with Euler's equation when the body fixed coordinate frame origin is not coincident with the center of mass of the body²

$$\dot{\mathbf{H}}_{sc,B} = \mathbf{L}_B + m_{sc} \ddot{\mathbf{r}}_{B/N} \times \mathbf{c} \quad (13)$$

where \mathbf{L}_B is the total external torque about point B . The definition of the angular momentum vector of the spacecraft about point B is

$$\mathbf{H}_{sc,B} = [I_{hub,B_c}] \boldsymbol{\omega}_{B/N} + m_{hub} \mathbf{r}_{B_c/B} \times \dot{\mathbf{r}}_{B_c/B} + \sum_{j=1}^{N_P} m_j \mathbf{r}_{P_{c,j}/B} \times \dot{\mathbf{r}}_{P_{c,j}/B} \quad (14)$$

Now the inertial time derivative of Eq. (14) is taken and yields

$$\dot{\mathbf{H}}_{sc,B} = [I_{hub,B_c}] \dot{\boldsymbol{\omega}}_{B/N} + \boldsymbol{\omega}_{B/N} \times [I_{hub,B_c}] \boldsymbol{\omega}_{B/N} + m_{hub} \mathbf{r}_{B_c/B} \times \ddot{\mathbf{r}}_{B_c/B} + \sum_{j=1}^{N_P} m_j \mathbf{r}_{P_{c,j}/B} \times \ddot{\mathbf{r}}_{P_{c,j}/B} \quad (15)$$

$\ddot{\mathbf{r}}_{P_{c,j}/B}$ is

$$\ddot{\mathbf{r}}_{P_{c,j}/B} = \mathbf{r}''_{P_{c,j}/B} + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \quad (16)$$

Incorporating Eq.- (16) into Eq. (15) results in

$$\begin{aligned} \dot{\mathbf{H}}_{sc,B} = & [I_{hub,B_c}] \dot{\boldsymbol{\omega}}_{B/N} + \boldsymbol{\omega}_{B/N} \times [I_{hub,B_c}] \boldsymbol{\omega}_{B/N} + m_{hub} \mathbf{r}_{B_c/B} \times \ddot{\mathbf{r}}_{B_c/B} \\ & + \sum_{j=1}^{N_P} m_j \mathbf{r}_{P_{c,j}/B} \times \left[\mathbf{r}''_{P_{c,j}/B} + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \right] \end{aligned} \quad (17)$$

Applying the parallel axis theorem the following inertia tensor terms are defined as

$$[I_{sc,B}] = [I_{hub,B}] + m_{hub}[\tilde{\mathbf{r}}_{B_c/B}][\tilde{\mathbf{r}}_{B_c/B}]^T + \sum_{j=1}^{N_P} m_j[\tilde{\mathbf{r}}_{P_{c,j}/B}][\tilde{\mathbf{r}}_{P_{c,j}/B}]^T \quad (18)$$

Taking the body-relative time derivative of Equation (18) yields

$$[I'_{sc,B}] = - \sum_{j=1}^{N_P} m_j \left([\tilde{\mathbf{r}}'_{P_{c,j}/B}][\tilde{\mathbf{r}}_{P_{c,j}/B}] + [\tilde{\mathbf{r}}_{P_{c,j}/B}][\tilde{\mathbf{r}}'_{P_{c,j}/B}] \right) \quad (19)$$

The Jacobi Identity, $(\mathbf{a} \times \mathbf{b}) \times \mathbf{c} = \mathbf{a} \times (\mathbf{b} \times \mathbf{c}) - \mathbf{b} \times (\mathbf{a} \times \mathbf{c})$, is used to combine terms and produce the following simplified equation

$$\begin{aligned} \dot{\mathbf{H}}_{sc,B} = & [I_{sc,B}]\dot{\boldsymbol{\omega}}_{B/N} + \boldsymbol{\omega}_{B/N} \times [I_{sc,B}]\boldsymbol{\omega}_{B/N} + [I'_{sc,B}]\boldsymbol{\omega}_{B/N} \\ & + \sum_{j=1}^{N_P} \left[m_j \mathbf{r}_{P_{c,j}/B} \times \mathbf{r}''_{P_{c,j}/B} + m_j \boldsymbol{\omega}_{B/N} \times \left(\mathbf{r}_{P_{c,j}/B} \times \mathbf{r}'_{P_{c,j}/B} \right) \right] \end{aligned} \quad (20)$$

Eqs. (13) and (20) are equated and yield

$$\begin{aligned} \mathbf{L}_B + m_{sc}\ddot{\mathbf{r}}_{B/N} \times \mathbf{c} = & [I_{sc,B}]\dot{\boldsymbol{\omega}}_{B/N} + \boldsymbol{\omega}_{B/N} \times [I_{sc,B}]\boldsymbol{\omega}_{B/N} + [I'_{sc,B}]\boldsymbol{\omega}_{B/N} \\ & + \sum_{j=1}^{N_P} \left[m_j \mathbf{r}_{P_{c,j}/B} \times \mathbf{r}''_{P_{c,j}/B} + m_j \boldsymbol{\omega}_{B/N} \times \left(\mathbf{r}_{P_{c,j}/B} \times \mathbf{r}'_{P_{c,j}/B} \right) \right] \end{aligned} \quad (21)$$

Finally, using tilde matrix and simplifying yields the modified Euler equation, which is the second EOM necessary to describe the motion of the spacecraft.

$$\begin{aligned} [I_{sc,B}]\dot{\boldsymbol{\omega}}_{B/N} = & -[\tilde{\boldsymbol{\omega}}_{B/N}][I_{sc,B}]\boldsymbol{\omega}_{B/N} - [I'_{sc,B}]\boldsymbol{\omega}_{B/N} \\ & - \sum_{j=1}^{N_P} \left(m_j [\tilde{\mathbf{r}}_{P_{c,j}/B}]\mathbf{r}''_{P_{c,j}/B} + m_j [\tilde{\boldsymbol{\omega}}_{B/N}][\tilde{\mathbf{r}}_{P_{c,j}/B}]\mathbf{r}'_{P_{c,j}/B} \right) + \mathbf{L}_B - m_{sc}[\tilde{\mathbf{c}}]\ddot{\mathbf{r}}_{B/N} \end{aligned} \quad (22)$$

Rearranging Eq. (22) to be in the same form as the previous sections results in

$$\begin{aligned} m_{sc}[\tilde{\mathbf{c}}]\ddot{\mathbf{r}}_{B/N} + [I_{sc,B}]\dot{\boldsymbol{\omega}}_{B/N} + \sum_{j=1}^{N_P} m_j [\tilde{\mathbf{r}}_{P_{c,j}/B}]\hat{\mathbf{p}}_j \ddot{\rho}_j = \\ - [\tilde{\boldsymbol{\omega}}_{B/N}][I_{sc,B}]\boldsymbol{\omega}_{B/N} - [I'_{sc,B}]\boldsymbol{\omega}_{B/N} - \sum_{j=1}^{N_P} m_j [\tilde{\boldsymbol{\omega}}_{B/N}][\tilde{\mathbf{r}}_{P_{c,j}/B}]\mathbf{r}'_{P_{c,j}/B} + \mathbf{L}_B \end{aligned} \quad (23)$$

1.1.3 Fuel Slosh Motion

Figure 1 shows that a single fuel slosh particle is free to move along its corresponding $\hat{\mathbf{p}}_j$ direction and this formulation is generalized to include N_P number of fuel slosh particles. The derivation begins with Newton's law for each fuel slosh particle:

$$m_j \ddot{\mathbf{r}}_{P_{c,j}/N} = \mathbf{F}_G + \mathbf{F}_C - k_j \rho_j \hat{\mathbf{p}}_j - c_j \dot{\rho}_j \hat{\mathbf{p}}_j \quad (24)$$

Where \mathbf{F}_C is the constraint force that maintains the fuel slosh mass to travel along the direction $\hat{\mathbf{p}}_j$. The forces due to the spring and damper are explicitly included in Eq. (24) and result in a restoring force and damping force. $\ddot{\mathbf{r}}_{P_{c,j}/N}$ is defined in the following equation.

$$\ddot{\mathbf{r}}_{P_{c,j}/N} = \ddot{\mathbf{r}}_{B/N} + \ddot{\mathbf{r}}_{P_{c,j}/B} \quad (25)$$

The inertial acceleration vector $\ddot{\mathbf{r}}_{P_{c,j}/B}$ is defined in Eq. (16). Plugging this definition into Eq. (24) results in

$$m_j \left[\ddot{\mathbf{r}}_{B/N} + \ddot{\rho}_j \hat{\mathbf{p}}_j + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \right] = \mathbf{F}_G + \mathbf{F}_C - k_j \rho_j \hat{\mathbf{p}}_j - c_j \dot{\rho}_j \hat{\mathbf{p}}_j \quad (26)$$

Equation (26) is the dynamical equation for a fuel slosh particle, however, the constraint force, \mathbf{F}_C , is undefined. Since the fuel slosh particle is free to move in the $\hat{\mathbf{p}}_j$ direction, the component of \mathbf{F}_C along the $\hat{\mathbf{p}}_j$ direction is zero. Leveraging this insight, Eq. (26) is projected into the $\hat{\mathbf{p}}_j$ direction by multiplying both sides of the equation by $\hat{\mathbf{p}}_j^T$.

$$m_j \left(\hat{\mathbf{p}}_j^T \ddot{\mathbf{r}}_{B/N} + \ddot{\rho}_j + 2\hat{\mathbf{p}}_j^T \boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \hat{\mathbf{p}}_j^T \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} + \hat{\mathbf{p}}_j^T \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \right) = \hat{\mathbf{p}}_j^T \mathbf{F}_G - k_j \rho_j - c_j \dot{\rho}_j \quad (27)$$

Moving the second order terms to the left hand side and introducing the tilde matrix notation yields the final equation needed to describe the motion of the spacecraft.

$$m_j \hat{\mathbf{p}}_j^T \ddot{\mathbf{r}}_{B/N} - m_j \hat{\mathbf{p}}_j^T [\tilde{\mathbf{r}}_{P_{c,j}/B}] \dot{\boldsymbol{\omega}}_{B/N} + m_j \ddot{\rho}_j = \hat{\mathbf{p}}_j^T \mathbf{F}_G - k_j \rho_j - c_j \dot{\rho}_j - 2m_j \hat{\mathbf{p}}_j^T [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{r}'_{P_{c,j}/B} - m_j \hat{\mathbf{p}}_j^T [\tilde{\boldsymbol{\omega}}_{B/N}] [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{r}_{P_{c,j}/B} \quad (28)$$

1.2 Derivation of Equations of Motion - Kane's Method

The choice of generalized coordinates and their respective generalized speeds are:

$$\mathbf{q} = \begin{bmatrix} \mathbf{r}_{B/N} \\ \boldsymbol{\sigma}_{B/N} \\ \rho_1 \\ \cdot \\ \rho_{N_P} \end{bmatrix} \quad \mathbf{u} = \begin{bmatrix} \dot{\mathbf{r}}_{B/N} \\ \boldsymbol{\omega}_{B/N} \\ \dot{\rho}_1 \\ \cdot \\ \dot{\rho}_{N_P} \end{bmatrix} \quad (29)$$

The necessary velocities needed to be defined are as follows

$$\dot{\mathbf{r}}_{B_c/N} = \dot{\mathbf{r}}_{B/N} + \boldsymbol{\omega}_{B/N} \times \mathbf{r}_{B_c/B} = \dot{\mathbf{r}}_{B/N} - [\tilde{\mathbf{r}}_{B_c/B}] \boldsymbol{\omega}_{B/N} \quad (30)$$

$$\dot{\mathbf{r}}_{C/N} = \dot{\mathbf{r}}_{B/N} + \dot{\mathbf{c}} \quad (31)$$

$$\boldsymbol{\omega}_{B/N} = \boldsymbol{\omega}_{B/N} \quad (32)$$

$$\dot{\mathbf{r}}_{P_{c,j}/N} = \dot{\mathbf{r}}_{B/N} + \mathbf{r}'_{P_{c,j}/B} + \boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B} = \dot{\mathbf{r}}_{B/N} + \dot{\rho}_j \hat{\mathbf{p}}_j - [\tilde{\mathbf{r}}_{P_{c,j}/B}] \boldsymbol{\omega}_{B/N} \quad (33)$$

Now the following partial velocity table can be created:

Table 2: Partial Velocity Table

r	$\mathbf{v}_r^{B_c}$	$\boldsymbol{\omega}_r^B$	$\mathbf{v}_r^{P_c}$
1 – 3	$[I_{3 \times 3}]$	$[0_{3 \times 3}]$	$[I_{3 \times 3}]$
4 – 6	$-\tilde{\mathbf{r}}_{B_c/B}$	$[I_{3 \times 3}]$	$-\tilde{\mathbf{r}}_{P_{c,j}/B}$
7 – N_P	$[0_{3 \times 1}]$	$[0_{3 \times 1}]$	$\hat{\mathbf{p}}_j$

An additional partial velocity that is needed is $[\mathbf{v}_{1-3}^C]$ for the external force applied on the spacecraft, \mathbf{F}_{ext} . Using Eq.(31) the following is defined:

$$[\mathbf{v}_{1-3}^C] = [I_{3 \times 3}] \quad (34)$$

Using these partial velocity definitions, the follow sections will step through the formulation for the translational, rotational and slosh EOMs developed using Kane's method.

1.2.1 Rigid Spacecraft Hub Translational Motion

Starting with the definition of a generalized force:

$$\mathbf{F}_r = \mathbf{v}_r^T \mathbf{F} \quad (35)$$

Using this definition the external force applied on the spacecraft for the translational equations is defined as:

$$\mathbf{F}_{1-3} = [\mathbf{v}_{1-3}^C]^T \mathbf{F}_{\text{ext}} = \mathbf{F}_{\text{ext}} \quad (36)$$

Using the definition of generalized inertia forces,

$$\mathbf{F}_r^* = \sum_r^N \left[\boldsymbol{\omega}_r^T \mathbf{T}^* + \mathbf{v}_r^T (-m_r \mathbf{a}_r) \right] \quad (37)$$

the inertia forces for the hub translational motion are defined as

$$\mathbf{F}_{1-3}^* = [\mathbf{v}_{1-3}^B]^T (-m_{\text{hub}} \ddot{\mathbf{r}}_{B_c/N}) + \sum_j^{N_P} [\mathbf{v}_{1-3}^{P_c}]^T (-m_j \ddot{\mathbf{r}}_{P_{c,j}/N}) = -m_{\text{hub}} \ddot{\mathbf{r}}_{B_c/N} + \sum_j^{N_P} -m_j \ddot{\mathbf{r}}_{P_{c,j}/N} \quad (38)$$

Finally, Kane's equation is:

$$\mathbf{F}_r + \mathbf{F}_r^* = 0 \quad (39)$$

therefore

$$\mathbf{F}_{\text{ext}} - m_{\text{hub}} \ddot{\mathbf{r}}_{B_c/N} + \sum_j^{N_P} -m_j \ddot{\mathbf{r}}_{P_{c,j}/N} = 0 \quad (40)$$

Expanding and rearranging results in

$$m_{\text{hub}} \ddot{\mathbf{r}}_{B_c/N} + \sum_j^{N_P} m_j (\ddot{\mathbf{r}}_{B/N} + \ddot{\mathbf{r}}_{P_{c,j}/B}) = \mathbf{F}_{\text{ext}} \quad (41)$$

Plugging Eq. (16) into Eq. (41) results in

$$m_{\text{hub}} (\ddot{\mathbf{r}}_{B_c/N} + \ddot{\mathbf{r}}_{B_c/B}) + \sum_j^{N_P} m_j \left[\ddot{\mathbf{r}}_{B/N} + \ddot{\mathbf{p}}_j \hat{\mathbf{p}}_j + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \right] = \mathbf{F}_{\text{ext}} \quad (42)$$

Combining like terms and rearranging results in

$$m_{sc}\ddot{\mathbf{r}}_{B/N} - m_{sc}[\tilde{\mathbf{c}}]\dot{\boldsymbol{\omega}}_{B/N} + \sum_{j=1}^{N_P} m_j \hat{\mathbf{p}}_j \ddot{\rho}_j = \mathbf{F}_{\text{ext}} - 2m_{sc}[\tilde{\boldsymbol{\omega}}_{B/N}]\mathbf{c}' - m_{sc}[\tilde{\boldsymbol{\omega}}_{B/N}][\tilde{\boldsymbol{\omega}}_{B/N}]\mathbf{c} \quad (43)$$

Which is identical to Eq. (12) found using Newtonian mechanics.

1.2.2 Rigid Spacecraft Hub Rotational Motion

The torque acting on the spacecraft, \mathbf{L}_B needs to be defined as a general active force. Using Eq. (35) active forces acting on the spacecraft for the rotational equations can be defined as:

$$\mathbf{F}_{4-6} = [\boldsymbol{\omega}_{4-6}^B]^T \mathbf{L}_B = \mathbf{L}_B \quad (44)$$

To define the generalized inertia forces, using Eq. (37) the definition of \mathbf{T}^* needs to be defined for a rigid body and applying it to the hub:

$$\mathbf{T}^* = -[I_{\text{hub},B}]\dot{\boldsymbol{\omega}}_{B/N} - [\tilde{\boldsymbol{\omega}}_{B/N}][I_{\text{hub},B}]\boldsymbol{\omega}_{B/N} \quad (45)$$

$$\begin{aligned} \mathbf{F}_{4-6}^* &= [\boldsymbol{\omega}_{4-6}^B]^T \mathbf{T}^* + [\mathbf{v}_{4-6}^{Bc}]^T (-m_{\text{hub}}\ddot{\mathbf{r}}_{Bc/N}) + \sum_j^{N_P} [\mathbf{v}_{4-6}^{Pc}]^T (-m_j\ddot{\mathbf{r}}_{Pc,j/N}) \\ &= -[I_{\text{hub},B}]\dot{\boldsymbol{\omega}}_{B/N} - [\tilde{\boldsymbol{\omega}}_{B/N}][I_{\text{hub},B}]\boldsymbol{\omega}_{B/N} - m_{\text{hub}}[\tilde{\mathbf{r}}_{Bc/B}]\ddot{\mathbf{r}}_{Bc/N} + \sum_j^{N_P} -[\tilde{\mathbf{r}}_{Pc,j/B}]^T (-m_j\ddot{\mathbf{r}}_{Pc,j/N}) \end{aligned} \quad (46)$$

Using Kane's equation, Eq. (39), the following equations of motion for the rotational dynamics are defined:

$$\mathbf{L}_B - [I_{\text{hub},B}]\dot{\boldsymbol{\omega}}_{B/N} - [\tilde{\boldsymbol{\omega}}_{B/N}][I_{\text{hub},B}]\boldsymbol{\omega}_{B/N} - m_{\text{hub}}[\tilde{\mathbf{r}}_{Bc/B}]\ddot{\mathbf{r}}_{Bc/N} + \sum_j^{N_P} -[\tilde{\mathbf{r}}_{Pc,j/B}](m_j\ddot{\mathbf{r}}_{Pc,j/N}) = 0 \quad (47)$$

Plugging in some definitions

$$\begin{aligned} [I_{\text{hub},B}]\dot{\boldsymbol{\omega}}_{B/N} + m_{\text{hub}}[\tilde{\mathbf{r}}_{Bc/B}]\ddot{\mathbf{r}}_{Bc/N} + \sum_j^{N_P} m_j[\tilde{\mathbf{r}}_{Pc,j/B}]\left[\ddot{\mathbf{r}}_{B/N} + \ddot{\rho}_j\hat{\mathbf{p}}_j + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{Pc,j/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{Pc,j/B} \right. \\ \left. + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{Pc,j/B})\right] = -[\tilde{\boldsymbol{\omega}}_{B/N}][I_{\text{hub},B}]\boldsymbol{\omega}_{B/N} + \mathbf{L}_B \end{aligned} \quad (48)$$

Combining like terms results in the same equation seen in Eq. (23) found using Newtonian mechanics.

$$\begin{aligned} m_{sc}[\tilde{\mathbf{c}}]\ddot{\mathbf{r}}_{B/N} + [I_{sc,B}]\dot{\boldsymbol{\omega}}_{B/N} + \sum_{j=1}^{N_P} m_j[\tilde{\mathbf{r}}_{Pc,j/B}]\hat{\mathbf{p}}_j\ddot{\rho}_j = \\ -[\tilde{\boldsymbol{\omega}}_{B/N}][I_{sc,B}]\boldsymbol{\omega}_{B/N} - [I'_{sc,B}]\boldsymbol{\omega}_{B/N} - \sum_{j=1}^{N_P} m_j[\tilde{\boldsymbol{\omega}}_{B/N}][\tilde{\mathbf{r}}_{Pc,j/B}]\mathbf{r}'_{Pc,j/B} + \mathbf{L}_B \end{aligned} \quad (49)$$

1.2.3 Fuel Slosh Motion

Following the similar pattern for translational and rotational equations the generalized active forces are defined:

$$\mathbf{F}_7 = \mathbf{v}_r^{P_c} \cdot (\mathbf{F}_G + \mathbf{F}_C - k\rho_j\hat{\mathbf{p}}_j - c\dot{\rho}_j\hat{\mathbf{p}}_j) = \hat{\mathbf{p}}_j^T \mathbf{F}_G - k\rho_j - c\dot{\rho}_j \quad (50)$$

The generalized inertia forces are defined as:

$$\mathbf{F}_7^* = \mathbf{v}_r^{P_c} \cdot (-m_j\ddot{\mathbf{r}}_{P_{c,j}/N}) = \hat{\mathbf{p}}_j^T (-m_j\ddot{\mathbf{r}}_{P_{c,j}/N}) \quad (51)$$

Using Kane's equation the following equations of motion are defined:

$$\begin{aligned} \hat{\mathbf{p}}_j^T \mathbf{F}_G - k\rho_j - c\dot{\rho}_j - m_j\hat{\mathbf{p}}_j^T \left[\ddot{\mathbf{r}}_{B/N} + \ddot{\rho}_j\hat{\mathbf{p}}_j + 2\boldsymbol{\omega}_{B/N} \times \mathbf{r}'_{P_{c,j}/B} + \dot{\boldsymbol{\omega}}_{B/N} \times \mathbf{r}_{P_{c,j}/B} \right. \\ \left. + \boldsymbol{\omega}_{B/N} \times (\boldsymbol{\omega}_{B/N} \times \mathbf{r}_{P_{c,j}/B}) \right] = 0 \quad (52) \end{aligned}$$

Rearranging and combining like terms results in:

$$\begin{aligned} m_j\hat{\mathbf{p}}_j^T \ddot{\mathbf{r}}_{B/N} - m_j\hat{\mathbf{p}}_j^T [\ddot{\mathbf{r}}_{P_{c,j}/B}] \dot{\boldsymbol{\omega}}_{B/N} + m_j\ddot{\rho}_j \\ = \hat{\mathbf{p}}_j^T \mathbf{F}_G - k_j\rho_j - c_j\dot{\rho}_j - 2m_j\hat{\mathbf{p}}_j^T [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{r}'_{P_{c,j}/B} - m_j\hat{\mathbf{p}}_j^T [\tilde{\boldsymbol{\omega}}_{B/N}] [\tilde{\boldsymbol{\omega}}_{B/N}] \mathbf{r}_{P_{c,j}/B} \quad (53) \end{aligned}$$

Which is identical to Eq. (28)!

2 Model Functions

This module is intended to be used an approximation of fuel slosh attached to the spacecraft. It is intended to have multiple fuel slosh particles attached to the spacecraft. Also it is recommended to attach at least 3 fuel slosh particles with different sloshing directions to get motion across all axes. Below is a list of functions that this model performs:

- Compute it's contributions to the mass properties of the spacecraft
- Provides matrix contributions for the back substitution method
- Compute it's derivatives for ρ , $\dot{\rho}$, and \dot{m}
- Adds energy and momentum contributions to the spacecraft

3 Model Assumptions and Limitations

Below is a summary of the assumptions/limitations:

- Is an approximation to sloshing fuel
- Is derived in such a manner that does not require constraints to be met
- A single fuel slosh particle can only move along one direction, $\hat{\mathbf{p}}_j$, as seen in Figure 1
- Multiple fuel slosh particles are not interconnected, each fuel slosh particle is attached the rigid body hub independently

- Only constant linear spring and damping terms
- The mass, spring and damping coefficients can be attenuated to approximate frequencies expected by the fuel slosh
- There are no travel limits for the fuel slosh therefore the particles could travel past the limits of the fuel tank boundary (this can be avoided by varying the mass and/or spring constant while considering the expected accelerations of the s/c to stay within the tank)
- The mass of the fuel slosh particles add to the total mass of the fuel tank
- This model could be used with other fuel slosh models like a pendulum based fuel slosh model

4 Test Description and Success Criteria

This test is located in `simulation/dynamics/FuelTank/UnitTest/test_fuelSloshParticleStateEffector.py`. In this integrated test there are three fuel slosh particles connected to the spacecraft hub. Depending on the scenario, there are different success criteria. These are outlined in the following subsections:

4.1 Gravity integrated test

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

- Conservation of orbital angular momentum
- Conservation of orbital energy
- Conservation of rotational angular momentum
- Conservation of rotational energy

4.2 No gravity integrated test

In this test, the spacecraft is placed in free space (no gravity) and has no damping in the fuel slosh particles. 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

4.3 Damping with no gravity integrated test

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

- Conservation of orbital angular momentum
- Conservation of orbital energy
- Conservation of rotational angular momentum

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 3- 7. Additionally, the error tolerances can be seen in Table 8. The error tolerance for the energy and momentum tests is $1e-10$ and that was chosen to ensure cross platform success of the test, however it is expected to get conservation of energy and momentum down to $1e-14$ or lower.

Table 3: 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 ²
r_BcB_B	CoM Location in \mathcal{B} frame	$[0.0 \ 0.0 \ 0.0]^T$	m

Table 4: Fuel Slosh Particle 1 Parameters

Name	Description	Value	Units
mass	mass	10.0	kg
k	Spring Constant	100.0	N-m/rad
c	Damping Term	0.0 (15.0 for Damping Case)	N-m-s/rad
r_PB_B	Slosh Equilibrium Location in \mathcal{B} frame	$[0.1 \ 0.0 \ -0.1]^T$	m
pHat_B	Slosh direction in \mathcal{B} frame	$\begin{bmatrix} \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \end{bmatrix}^T$	1

Table 5: Fuel Slosh Particle 2 Parameters

Name	Description	Value	Units
mass	mass	10.0	kg
k	Spring Constant	100.0	N-m/rad
c	Damping Term	0.0 (17.0 for Damping Case)	N-m-s/rad
r_PB_B	Slosh Equilibrium Location in \mathcal{B} frame	$[0.0 \ 0.0 \ 0.1]^T$	m
pHat_B	Slosh direction in \mathcal{B} frame	$\begin{bmatrix} \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix}^T$	1

Table 6: Fuel Slosh Particle 3 Parameters

Name	Description	Value	Units
mass	mass	10.0	kg
k	Spring Constant	100.0	N-m/rad
c	Damping Term	0.0 (11.0 for Damping Case)	N-m-s/rad
r_PB_B	Slosh Equilibrium Location in \mathcal{B} frame	$[-0.1 \ 0.0 \ 0.1]^T$	m
pHat_B	Slosh direction in \mathcal{B} frame	$\left[-\frac{\sqrt{3}}{3} \ -\frac{\sqrt{3}}{3} \ \frac{\sqrt{3}}{3}\right]^T$	1

Table 7: Initial Conditions

Name	Description	Value	Units
(Particle 1) rhoInIt	(Particle 1) Initial ρ	0.05	m
(Particle 1) rhoDotInIt	(Particle 1) Initial $\dot{\rho}$	0.0	m/s
(Particle 2) rhoInIt	(Particle 2) Initial ρ	-0.025	m
(Particle 2) rhoDotInIt	(Particle 2) Initial $\dot{\rho}$	0.0	m/s
(Particle 3) rhoInIt	(Particle 3) Initial ρ	-0.015	m
(Particle 3) rhoDotInIt	(Particle 3) Initial $\dot{\rho}$	0.0	m/s
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)	$[0.5 \ 0.4 \ -0.7]^T$	m
v_CN_NInIt	Initial Velocity of S/C (no gravity)	$[0.1 \ -0.5 \ 0.3]^T$	m/s
sigma_BNInIt	Initial MRP of \mathcal{B} frame	$[0.0 \ 0.0 \ 0.0]^T$	1
omega_BN_BInIt	Initial Angular Velocity of \mathcal{B} frame	$[0.1 \ -0.1 \ 0.1]^T$	rad/s

Table 8: Error Tolerance - Note: Relative Tolerance is $\text{abs}\left(\frac{\text{truth}-\text{value}}{\text{truth}}\right)$

Test	Relative Tolerance
Energy and Momentum Conservation	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. An additional note: the angular momentum plots are plotting the change in the components of the angular momentum vector in the inertial frame. The individual components are not labeled because the goal is for each component to show conservation therefore the individual components do not have separate information needing to be specified.

6.1 Gravity with no damping scenario

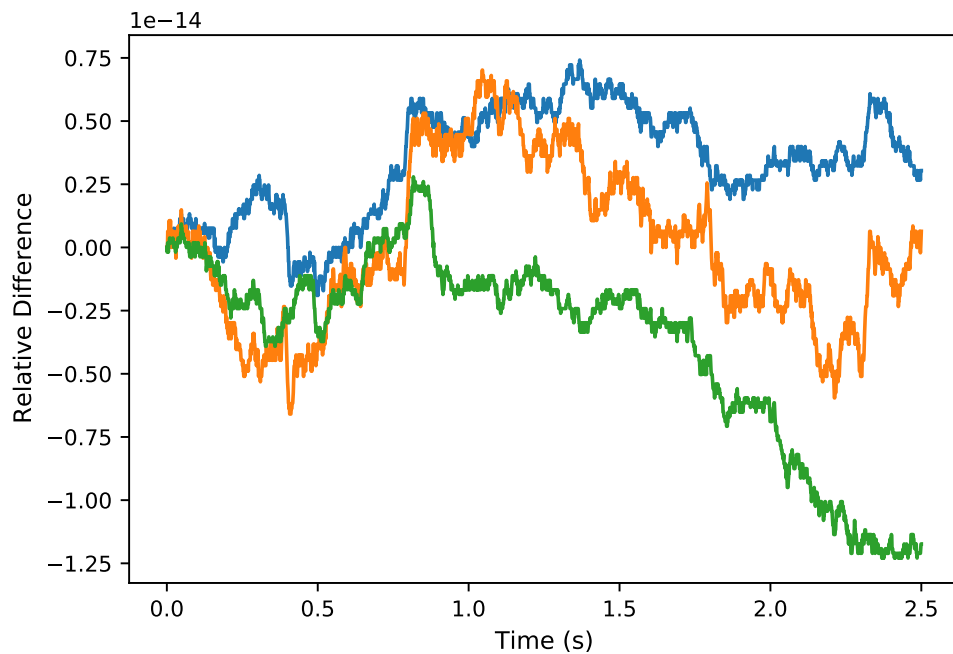


Fig. 2: Change in Orbital Angular Momentum Gravity

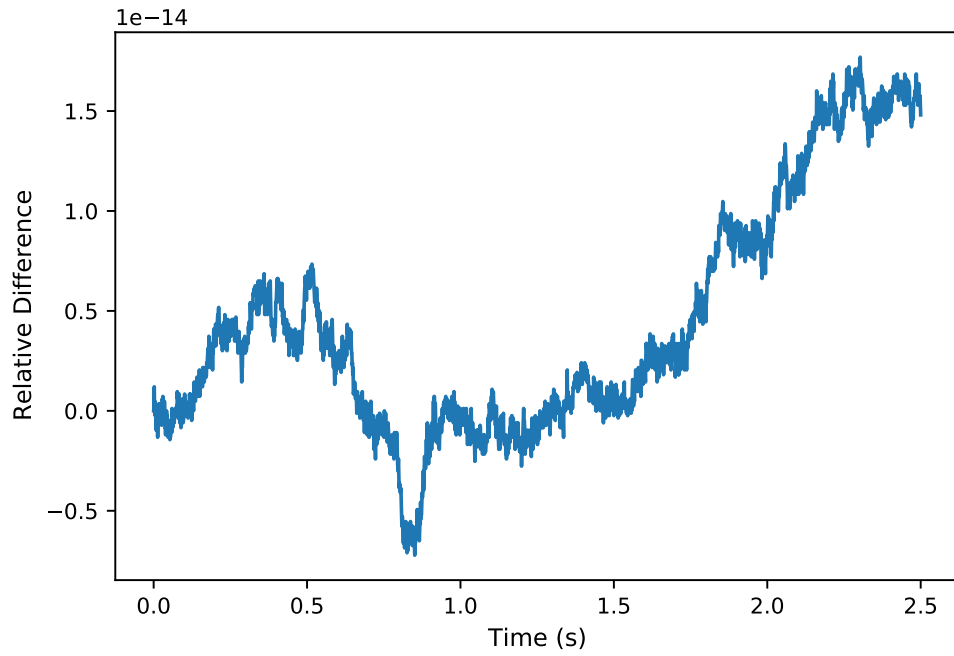


Fig. 3: Change in Orbital Energy Gravity

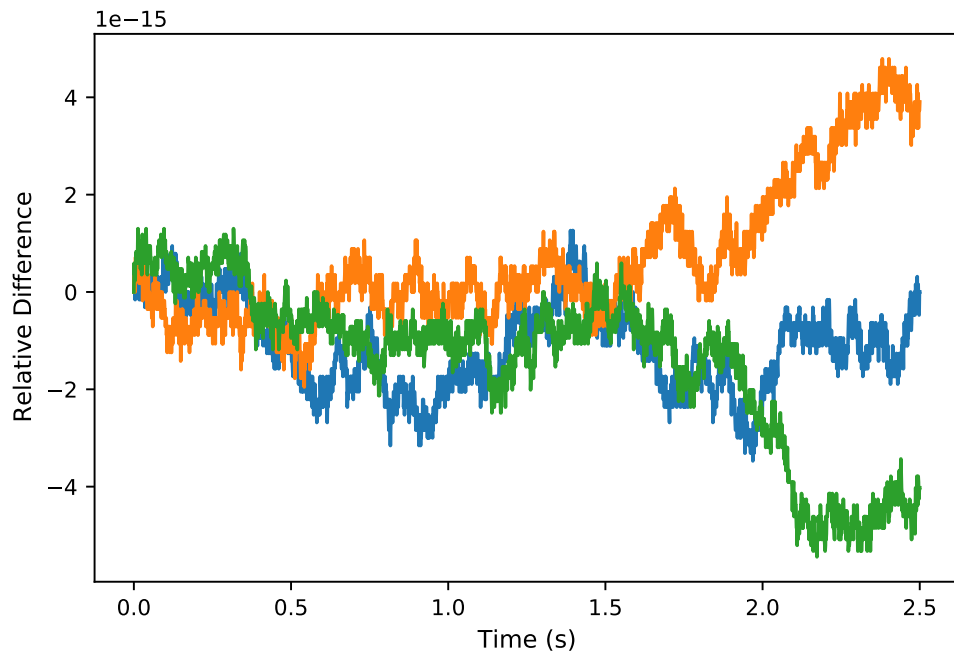


Fig. 4: Change In Rotational Angular Momentum Gravity

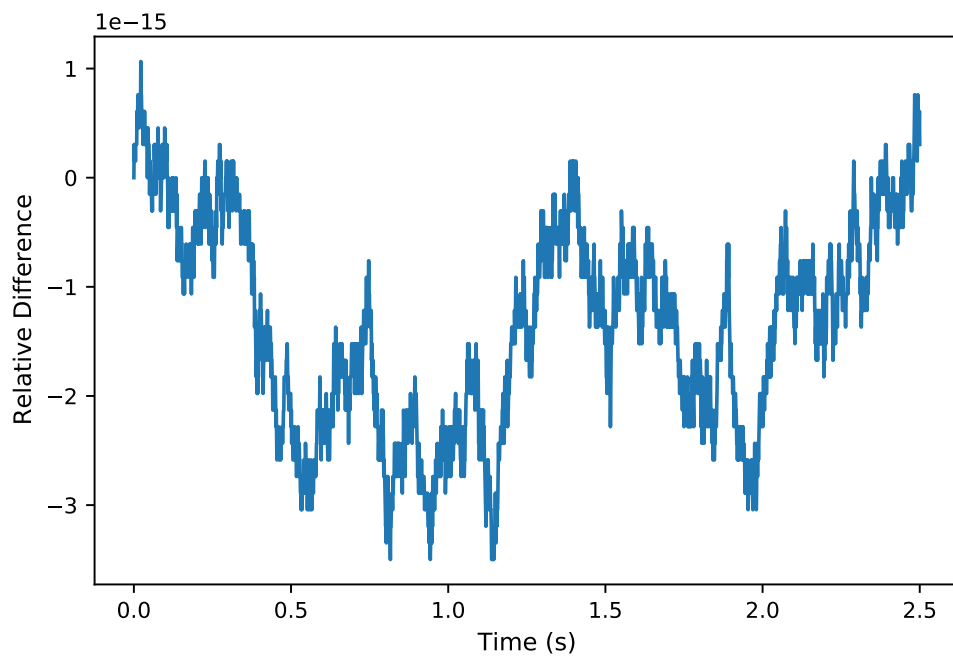


Fig. 5: Change In Rotational Energy Gravity

6.2 No Gravity with no damping scenario

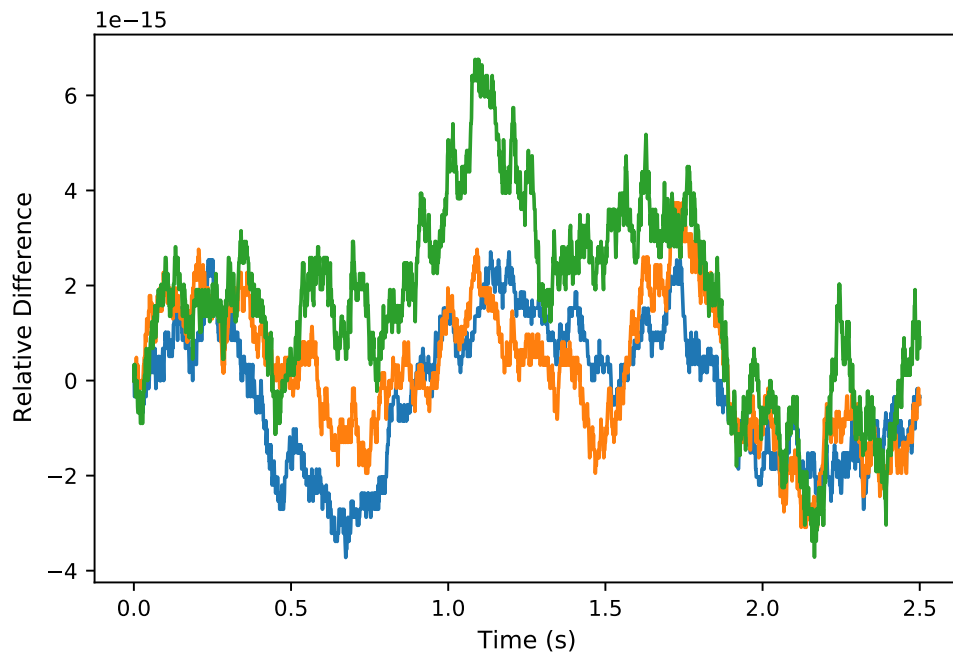


Fig. 6: Change In Orbital Angular Momentum No Gravity

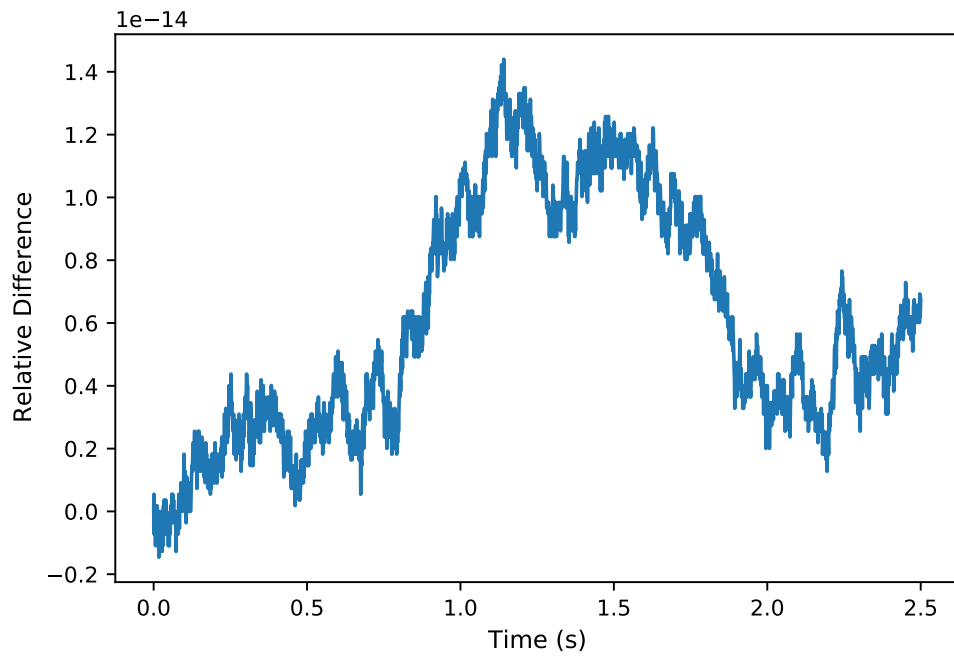


Fig. 7: Change In Orbital Energy No Gravity

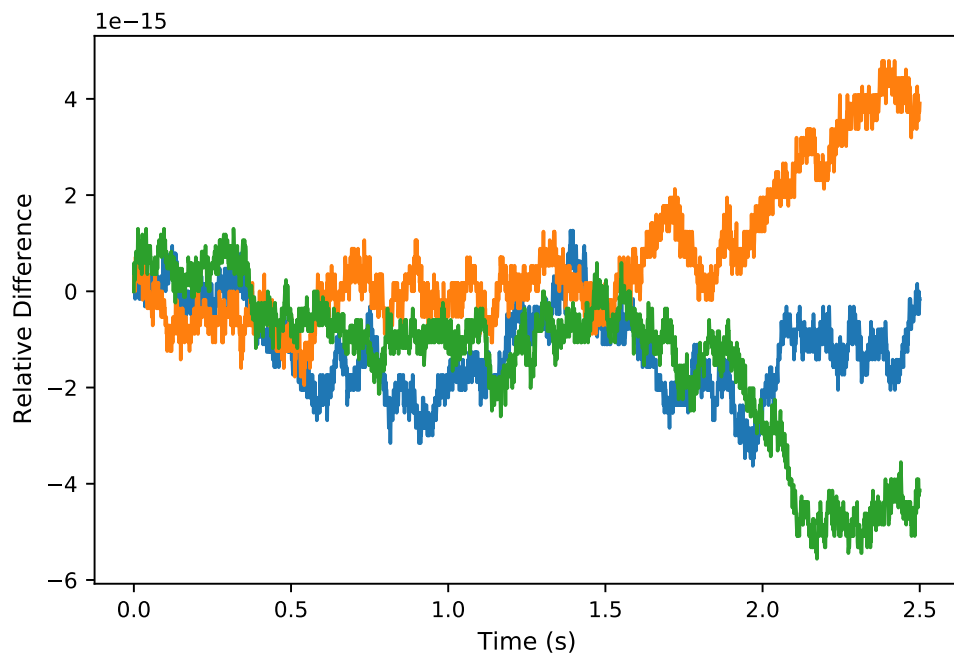


Fig. 8: Change In Rotational Angular Momentum No Gravity

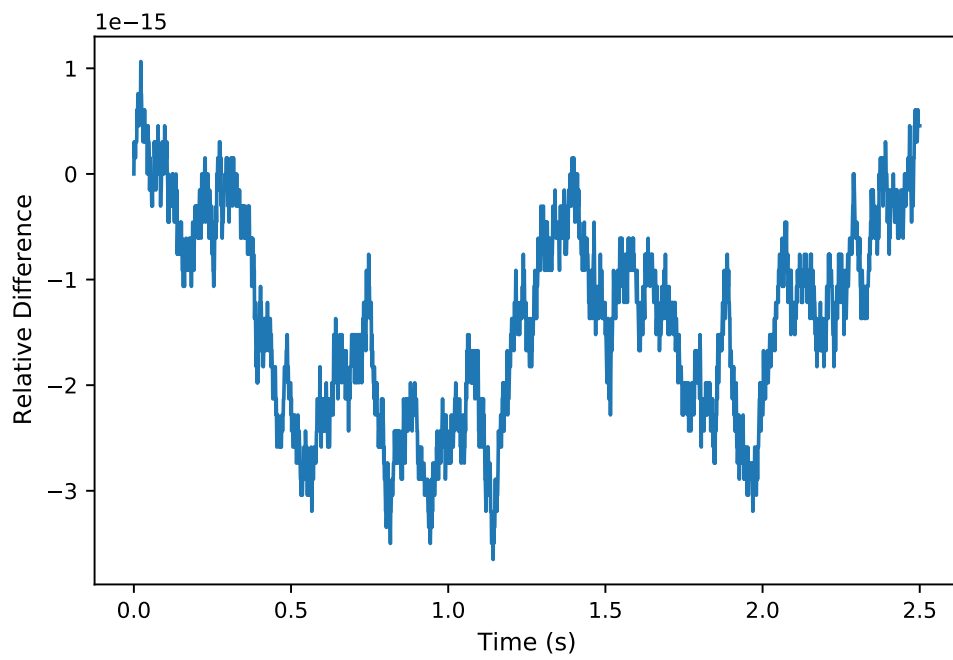


Fig. 9: Change In Rotational Energy No Gravity

6.3 Damping with no gravity scenario

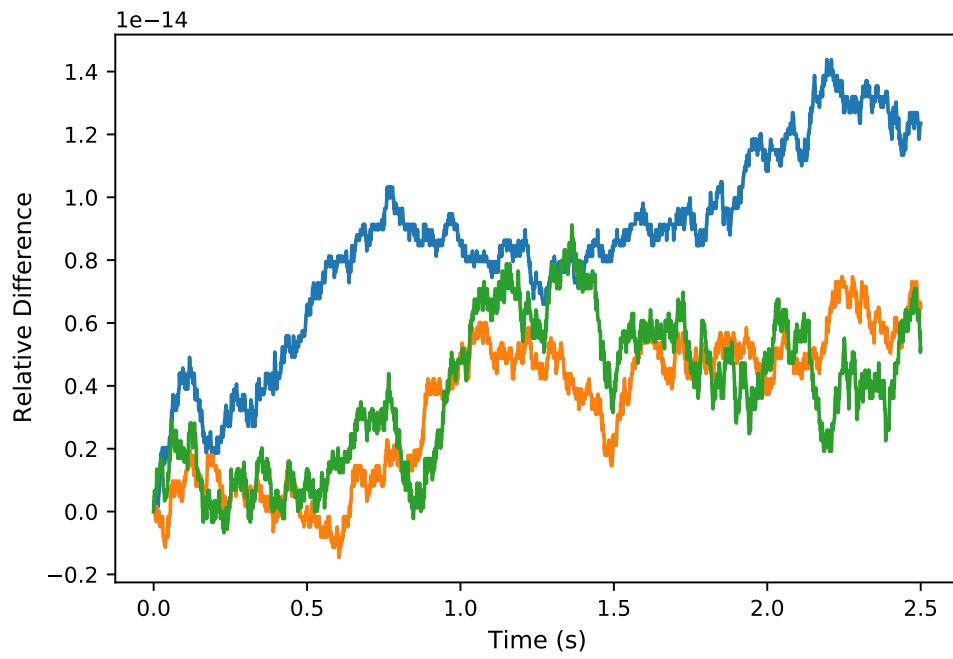


Fig. 10: Change In Orbital Angular Momentum Damping

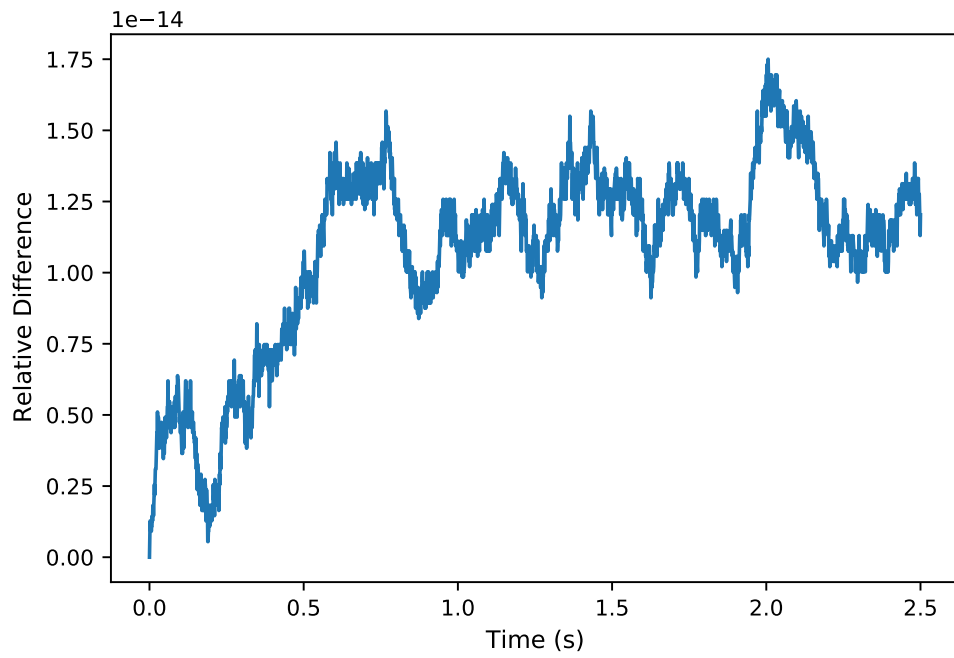


Fig. 11: Change In Orbital Energy Damping

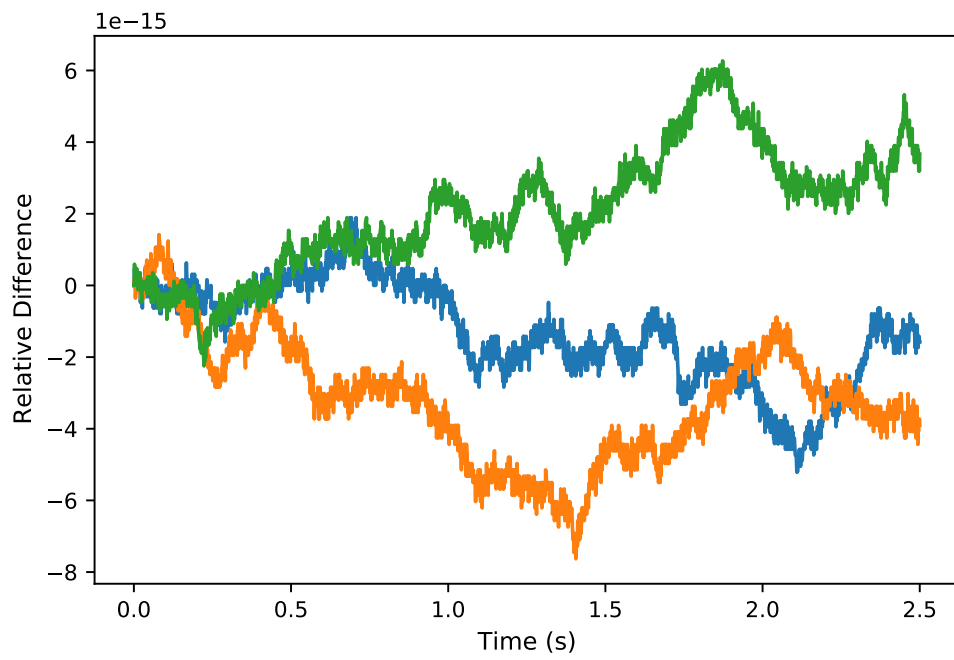


Fig. 12: Change In Rotational Angular Momentum Damping

7 User Guide

This section is to outline the steps needed to setup a Fuel Slosh State Effector in python using Basilisk.

1. Import the linearSpringMassDamper class:
`from Basilisk.simulation import linearSpringMassDamper`
2. Create an instantiation of a linear spring mass damper particle:
`particle1 = linearSpringMassDamper.LinearSpringMassDamper()`
3. Define all physical parameters for a linear spring mass damper particle. For example:
`particle1.r_PB_B = [[0.1], [0], [-0.1]]` Do this for all of the parameters for a linear spring mass damper particle seen in the public variables in the .h file.
4. Define the initial conditions of the states:
`particle1.rhoInnit = 0.05 particle1.rhoDotInnit = 0.0`
5. Define a unique name for each state:
`particle1.nameOfRhoState = "linearSpringMassDamperRho" particle1.nameOfRhoDotState = "linearSpringMassDamperRhoDot"`
6. Finally, add the particle to your spacecraft:
`scObject.addStateEffector(particle1)`. See spacecraft documentation on how to set up a spacecraft 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.
- [2] Hanspeter Schaub and John L. Junkins. *Analytical Mechanics of Space Systems*. AIAA Education Series, Reston, VA, 3rd edition, 2014.