Created in COMSOL Multiphysics 6.2

Dynamics of a Roller Chain Sprocket Assembly

Introduction

Chain drives are used for transmitting power from one shaft to another, located at some distance. This example simulates the dynamics of a chain sprocket assembly in 2D. The geometry consists of a roller chain wrapped around two sprockets. Both chain links and sprockets are assumed to be rigid. An angular velocity is prescribed at the driver sprocket.

The geometry of the chain sprocket assembly is created using built-in geometry parts. The **Chain Drive** node in the Multibody Dynamics interface is used for setting up the entire model. Using a transient study, the dynamics of the system is analyzed for two cases: when the driven sprocket is unloaded, and when it is loaded by a counteracting external torque. In the latter case, the driven sprocket is also assigned an additional moment of inertia. The results show comparisons of chain link motion, contact forces, and other results.

Model Definition

The model geometry consists of a chain wrapped around two sprockets in 2D, as shown in Figure 1.

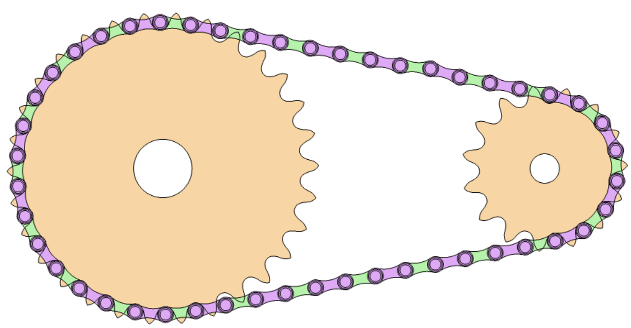


Figure 1: Geometry of a roller chain sprocket assembly.

The chain is assumed to be of roller type, and composed of a number of link plates. A typical roller chain has two different types of link plates: roller plates and pin plates. Elastic bushings are used to reduce vibrations in the system. These plates are connected in such a way that the relative rotation between them is unrestricted. Figure 2 shows an enlarged view of a chain link.

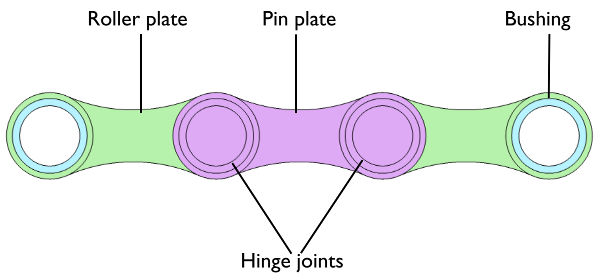


Figure 2: Enlarged view of a chain link. A chain is formed by assembling roller plates and pin plates alternately.

CHAIN AND SPROCKET PARAMETERS

The distance between two adjacent links is called *pitch*. In this example, the pitch is 0.25 in. Remaining geometric dimensions of the link plates are taken as standard, and parameterized as a function of the pitch. Table 1 lists the chain parameters.

The two sprockets have 30 and 15 teeth, respectively. They are located at a distance of 3 in. Each sprocket has a bore at its center, which enables mounting of the sprocket on other mechanical components such as shafts. Table 2 lists the sprocket parameters.

TABLE 1: CHAIN PARAMETERS

PARAMETER	NAME	VALUE
Pitch	p	0.25 in
Roller diameter to pitch ratio	Dr	0.52
Pin diameter to pitch ratio	Dp	0.362
Bushing diameter to pitch ratio	Db	0.45
Minimum link plate width to roller diameter ratio	Wl	0.6

TABLE 2: SPROCKET PARAMETERS

PARAMETER	NAME	VALUE
Pitch	p	0.25 in
Number of teeth, first sprocket	$n1$	30
Number of teeth, second sprocket	$n2$	15
Sprockets center distance	cd	3 in
Bore diameter to pitch diameter ratio for both sprockets	Dbr	0.2

MATERIALS

Both chain and sprockets are made of structural steel. They are modeled as rigid, and only the mass density of the steel is of relevance.

CHAIN DRIVE

The assembly of the chain and sprockets is modeled using the **Chain Drive** node. For a selected geometry part, this node automatically creates rigid domains, attachments and hinge joints which can be used to analyze the roller chain assembly.

SELECTION SETTINGS

For automatic generation of physics nodes, you need to select a geometry of the chain sprocket assembly from the **Part Library** of COMSOL Multiphysics. You can also create your own geometry, however the geometry requires domain and boundary selections to be used as inputs for automatic creation of other physics nodes. In this example, the following selections are used to create physics nodes using the **Chain Drive** node.

- Links: This is a domain selection containing all chain link domains. The selection is used for creating a **Rigid Material** node for each of the link plates.
- Sprockets: This is a domain selection containing both sprocket domains. The selection is used for creating a **Rigid Material** node for each of the sprockets.
- Pin Inner Boundaries: This is a boundary selection containing the inner boundaries of all pin plates. The selection is used for creating an **Attachment** node for each of the pin plates.
- Roller Inner Boundaries: This is a boundary selection containing the inner boundaries of the roller plates. The selection is used for creating an **Attachment** node for each of the roller plates, and it is located at same geometrical position as the Pin Inner Boundaries (Figure 4). Attachments created for the pin and roller plates are used as **Source** and **Destination** in **Hinge Joint** nodes.
- Roller Outer Boundaries: This boundary selection contains the outer surfaces of all roller plates. The selection is used for modeling contact between links and sprockets, as shown in Figure 5.

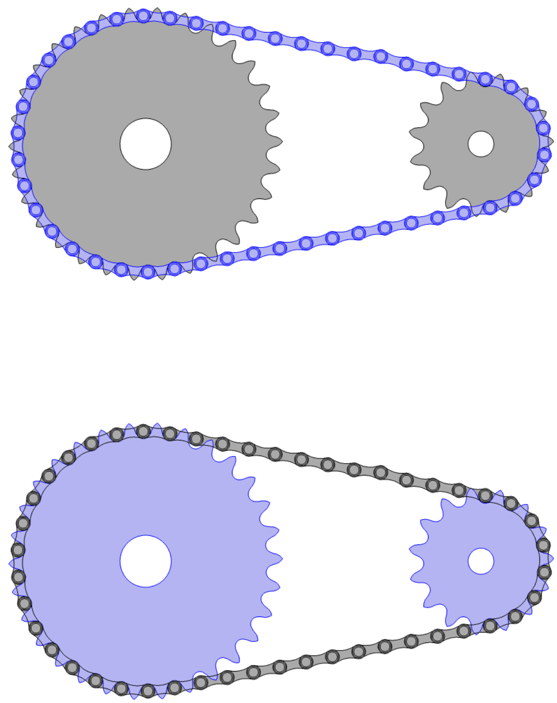


Figure 3: Links and Sprockets selections for creating rigid domains.

- Sprocket Outer Boundaries: This boundary selection contains the outer surfaces of the sprockets. As shown in Figure 5, these are the boundaries which come in contact with chain rollers.
- Sprocket Inner Boundaries: This boundary selection contains the inner surfaces of the sprockets, as shown in Figure 6. It is used for creating attachments and hinge joints for mounting the sprockets onto shafts.

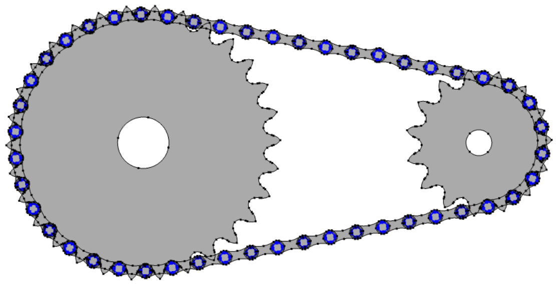


Figure 4: The Pin Inner Boundaries selection for creating attachments.

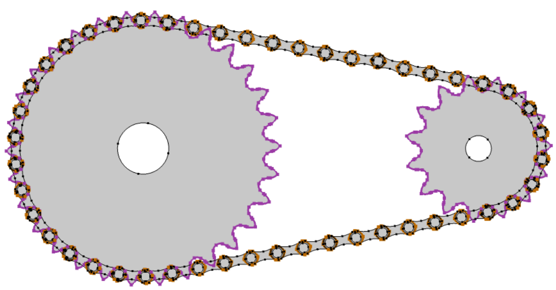


Figure 5: The Roller Outer Boundaries and Sprocket Outer Boundaries selections, used for rigid contact modeling.

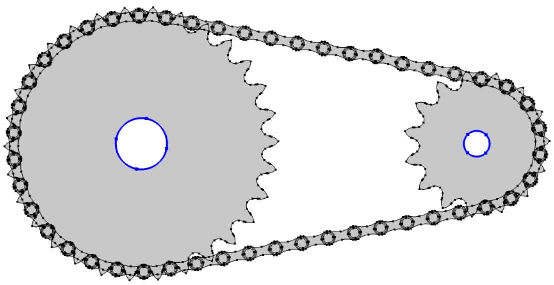


Figure 6: The Sprocket Inner Boundaries selection for creating attachments and hinge joints to mount the sprockets onto shafts.

Additional details about the **Chain Drive** functionality can be found in the *Multibody Dynamics Module User's Guide*.

Triangular mesh created on sprockets as well as chain links as shown in Figure 7

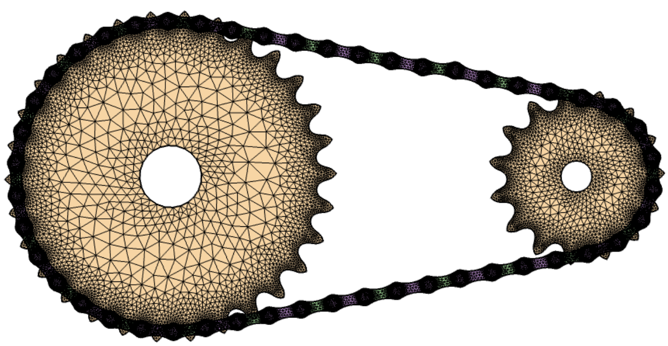


Figure 7: Finite element mesh created on sprockets and links.

BOUNDARY CONDITIONS

An angular velocity of 10 rad/s is prescribed on the left sprocket, which acts as the driver for the mechanism. The system is analyzed for two conditions of driven sprocket. In the first case, the driven sprocket is unloaded. In the second case, an external, counteracting torque of 0.01 Nm is applied, and an external moment of inertia of 10^{-5} kgm^2 is assigned to the driven sprocket.

STUDY

A Time Dependent study is used to analyze the chain drive. The analysis is performed for a duration of 0.3 s. The load path, contact forces, joint forces, and other results, are analyzed.

Results and Discussion

Figure 8 shows the displacement in the chain sprocket assembly, when the driven sprocket is unloaded.

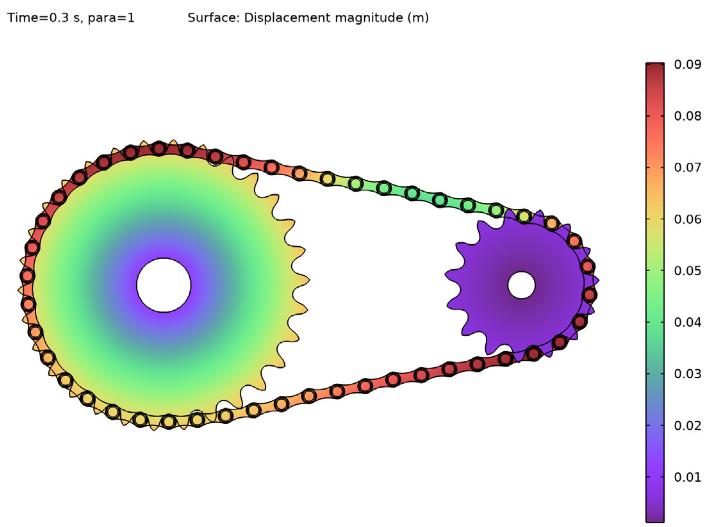
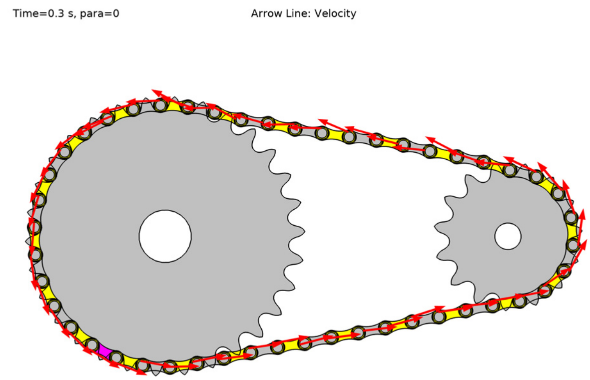


Figure 8: Displacement of chain links and sprockets at $t = 0.3$ s.

In Figure 9, velocity arrows show the direction and magnitude of the link motion for the unloaded and loaded cases.



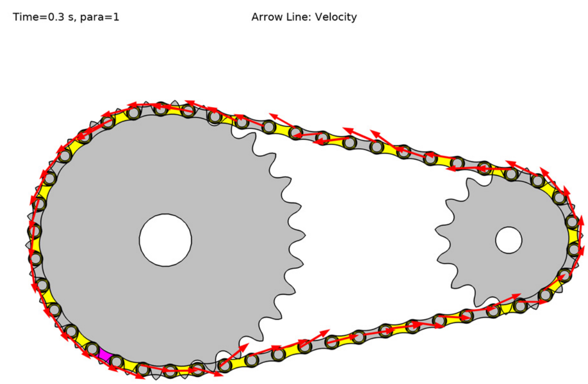


Figure 9: The motion of the chain links, illustrated by velocity arrows for the unloaded (top) and loaded (bottom) cases.

Structural contact between the rigid sprockets and the chain is modeled using a penalty based formulation. Figure 10 shows the contact forces on the chain links.

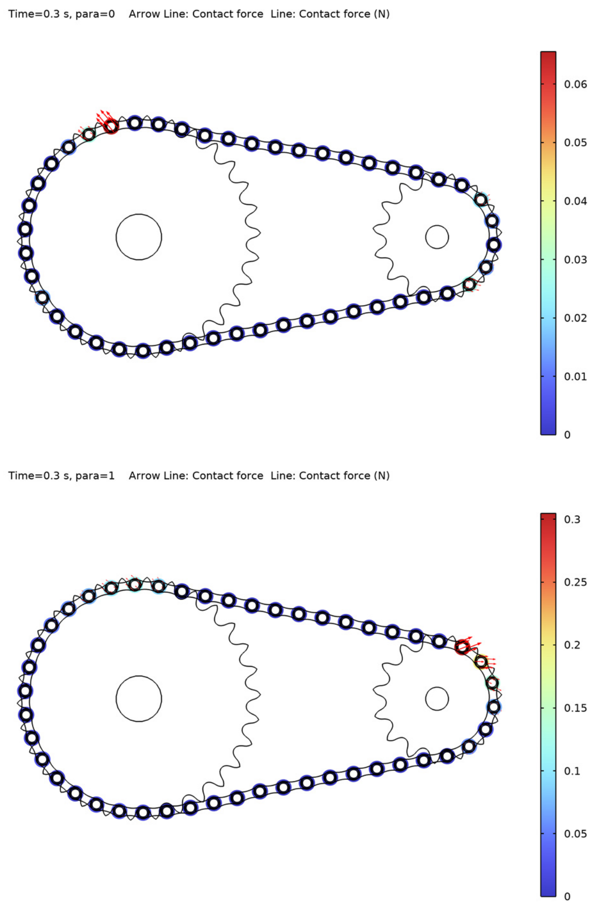


Figure 10: Contact forces for (a) unloaded and (b) loaded conditions.

The rotation of a sample link joint is plotted in Figure 11. In Figure 12, the variation of joint force with time is shown for the same link.

The dynamics of the system is controlled by the angular velocity prescribed on the driver sprocket. The chain transmits the motion to the second (driven) sprocket by a continuous engage-and-disengage mechanism. The rotation, angular velocity, and angular acceleration of the driven and driver sprockets are plotted in Figure 13, Figure 14 and Figure 15 respectively. Results from both the unloaded and loaded cases are shown.

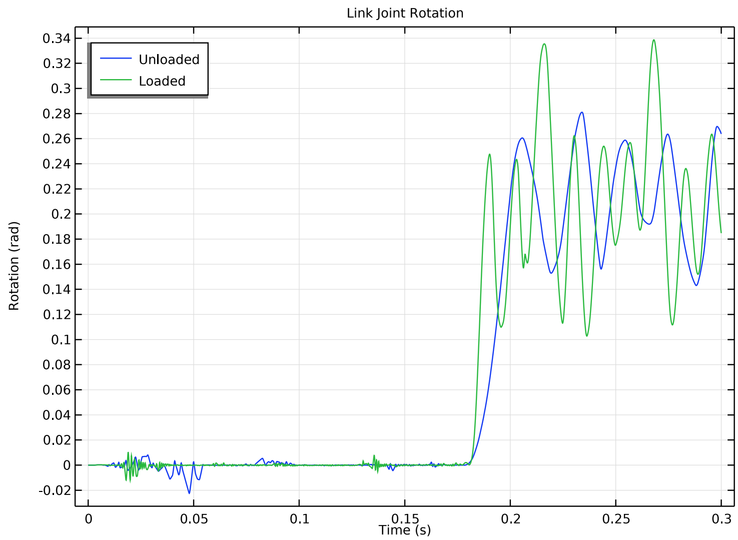


Figure 11: Rotation of a sample link joint, as a function of time.

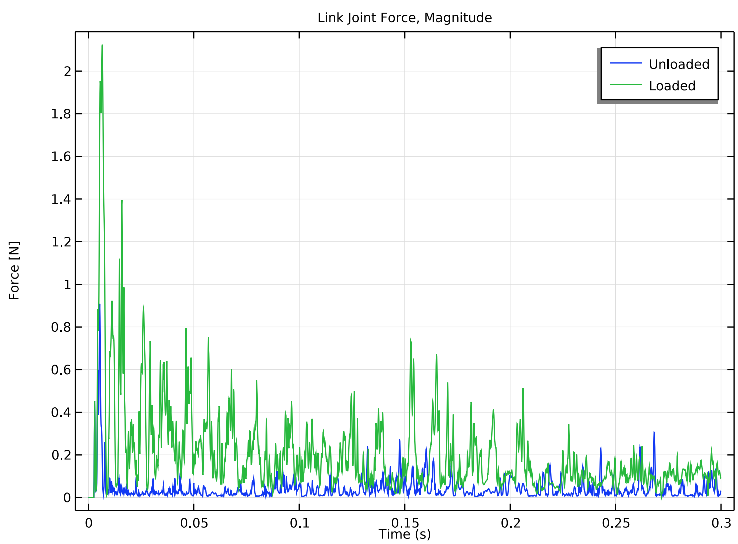


Figure 12: Variation of force with time, in a sample link joint.

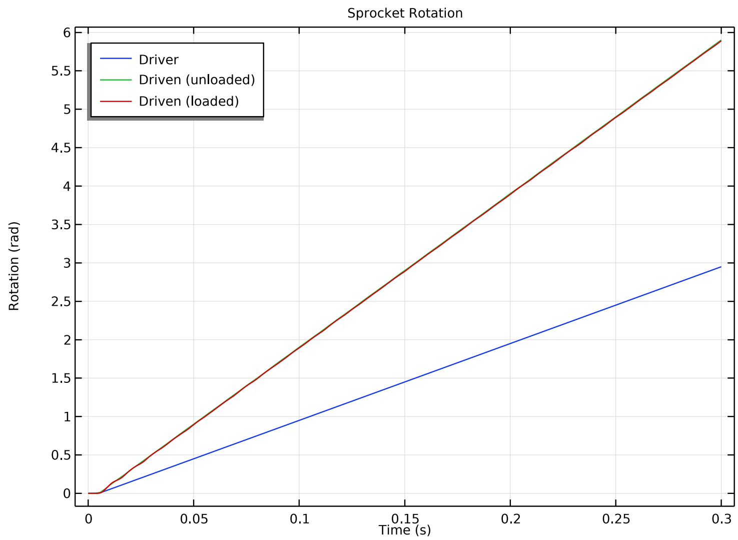


Figure 13: Sprocket rotation as a function of time.

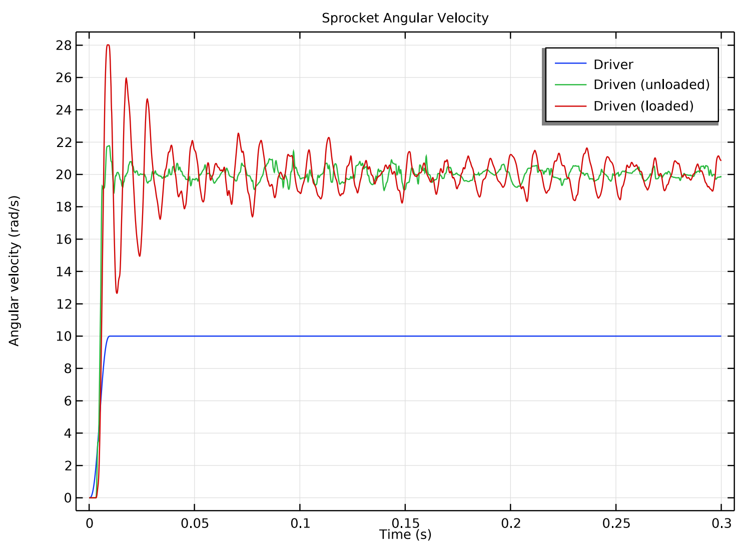


Figure 14: Driver and driven sprocket angular velocity, for the unloaded and loaded cases.

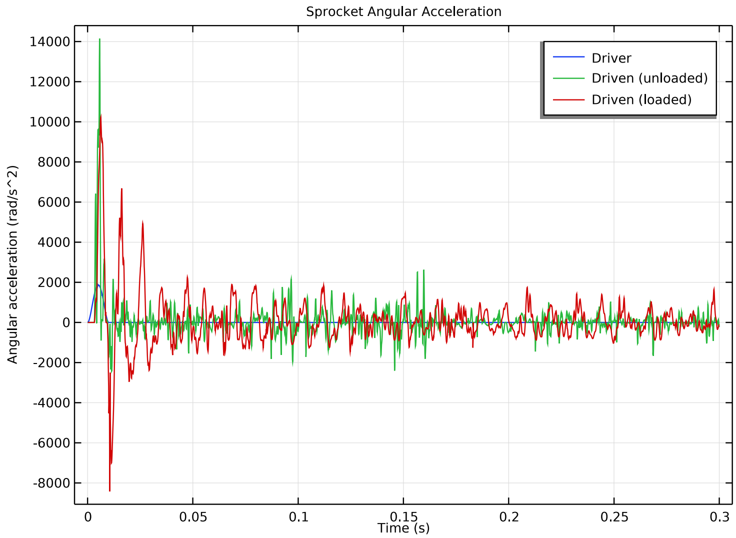


Figure 15: Driver and driven sprocket angular acceleration, for the unloaded and loaded cases.

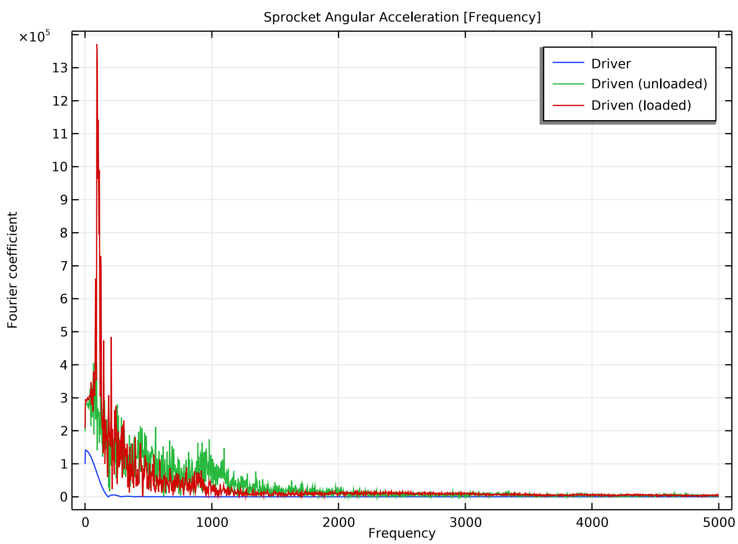


Figure 16: Frequency response of driver and driven sprocket angular acceleration for unloaded and loaded conditions.

Notes About the COMSOL Implementation

- To build a chain drive system geometry, you can import a roller chain sprocket assembly part from the **Part Library**, and customize it by changing its input parameters.
- **Chain Drive** node operates on the geometry in the assembly state.
- **Chain Drive** node creates new physics nodes from selections available in geometry. If you are using part imported from the **Part Library**, select the check box in **Geometry** to keep noncontributing selections. If you are building a geometry of a roller chain and sprocket assembly, you also need to create appropriate selections for the **Chain Drive** node to operate.
- When one or more selection inputs of **Chain Drive** node change, the selections of the physics nodes created by the **Chain Drive** node also change. Hence these nodes have to be deleted and recreated. This is indicated by a warning node appearing under the **Chain Drive** node. In that case, you need to press the **Create Links and Joints** button. This will automatically create new groups of physics nodes in accordance with the changed selection inputs.

Application Library path: `Multibody_Dynamics_Module/Tutorials,_Transmission/roller_chain_dynamics`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **Structural Mechanics>Multibody Dynamics (mbd)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Time Dependent**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
omega	10[rad/s]	10 rad/s	Angular velocity of drive shaft
T_ext	0.01[N*m]	0.01 N·m	External torque
I_ext	1e-5[kg*m^2]	1E-5 kg·m²	External moment of inertia
kb	1e5[N/m]	1E5 N/m	Spring constant, bushing
cb	1e5[N*s/m]	1E5 N·s/m	Damping coefficient, bushing
para	0	0	Load parameter

DEFINITIONS

Step 1 (step1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>Step**.

2 In the **Settings** window for **Step**, locate the **Parameters** section.

3 In the **Location** text field, type `5[ms]`.

4 Click to expand the **Smoothing** section. In the **Size of transition zone** text field, type `1e-2`.

5 Right-click **Step 1 (step1)** and choose **Duplicate**.

Step 2 (step2)

1 In the **Model Builder** window, click **Step 2 (step2)**.

2 In the **Settings** window for **Step**, locate the **Parameters** section.

3 In the **Location** text field, type `15[ms]`.

PART LIBRARIES

1 In the **Home** toolbar, click **Windows** and choose **Part Libraries**.

2 In the **Part Libraries** window, select **Multibody Dynamics Module>2D>Roller Chains>roller_chain_sprocket_assembly_2d** in the tree.

3 Click **Add to Geometry**.

4 In the **Select Part Variant** dialog box, select **Specify sprocket center distance** in the **Select part variant** list.

5 Click **OK**.

GEOMETRY 1

Roller Chain Sprocket (2D) 1 (pi1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Roller Chain Sprocket (2D) 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, locate the **Selection Settings** section.

3 Select the **Keep noncontributing selections** check box.

4 Click **Build Selected**.

Form Union (fin)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.

3 From the **Action** list, choose **Form an assembly**.

4 Clear the **Create pairs** check box.

5 Click **Build Selected**.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Built-in>Structural steel**.

4 Click **Add to Component** in the window toolbar.

5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MULTIBODY DYNAMICS (MBD)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Multibody Dynamics (mbd)**.

2 In the **Settings** window for **Multibody Dynamics**, locate the **Thickness** section.

3 In the d text field, type `2[mm]`.

Chain Drive 1

1 In the **Physics** toolbar, click **Global** and choose **Chain Drive**.

2 In the **Settings** window for **Chain Drive**, locate the **Chain Settings** section.

3 From the **Sprocket type** list, choose **Rigid**.

4 In the p_c text field, type `mbd.cdr1.Eequ*(0.1*mbd.diag)/1e5`.

5 Locate the **Joint Settings** section. From the **Joint type** list, choose **Elastic**.

Joint Elasticity 1

1 In the **Model Builder** window, click **Joint Elasticity 1**.

2 In the **Settings** window for **Joint Elasticity**, locate the **Spring** section.

3 In the $\mathbf{k}_u$ text field, type `kb`.

4 Locate the **Viscous Damping** section. In the $\mathbf{c}_u$ text field, type `cb`.

Chain Drive 1

Click **Create Links and Joints** in the window toolbar.

cdr1: Sprocket

In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)>cdr1: Sprocket** node.

Rigid Domain: Sprocket 2 (cdr1)

In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)>cdr1: Sprocket>Rigid Domain: Sprocket 2 (cdr1)** node, then click **Rigid Domain: Sprocket 2 (cdr1)**.

Mass and Moment of Inertia 1

1 In the **Physics** toolbar, click **Attributes** and choose **Mass and Moment of Inertia**.

2 In the **Settings** window for **Mass and Moment of Inertia**, locate the **Mass and Moment of Inertia** section.

3 In the I_z text field, type `I_ext*para`.

Hinge Joint: Sprocket: 1 (cdr1)

In the **Model Builder** window, expand the **Component 1 (comp1)>Multibody Dynamics (mbd)>cdr1: Sprocket>Hinge Joint: Sprocket: 1 (cdr1)** node, then click **Hinge Joint: Sprocket: 1 (cdr1)**.

Prescribed Motion 1

1 In the **Physics** toolbar, click **Attributes** and choose **Prescribed Motion**.

2 In the **Settings** window for **Prescribed Motion**, locate the **Prescribed Rotational Motion** section.

3 From the **Prescribed motion through** list, choose **Angular velocity**.

4 In the ω_p text field, type `omega*step1(t)`.

Hinge Joint: Sprocket: 2 (cdr1)

In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)> cdr1: Sprocket** click **Hinge Joint: Sprocket: 2 (cdr1)**.

Applied Force and Moment 1

1 In the **Physics** toolbar, click **Attributes** and choose **Applied Force and Moment**.

2 In the **Settings** window for **Applied Force and Moment**, locate the **Applied On** section.

3 From the list, choose **Joint**.

4 Locate the **Applied Force and Moment** section. In the *M* text field, type `-T_ext*step2(t)*para`.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
Flj_1	sqrt(mbd.cdr1hgj1.F_elx^2+ mbd.cdr1hgj1.F_ely^2)	N	Link joint force (elastic) , joint 1

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,1e-4,0.3)`.

4 From the **Tolerance** list, choose **User controlled**.

5 In the **Relative tolerance** text field, type `0.01`.

6 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

7 Click **Add**.

8 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
para (Load parameter)	0 1	

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Time-Dependent Solver 1**.
3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.
4 From the **Steps taken by solver** list, choose **Intermediate**.
5 In the **Model Builder** window, expand the **Study 1>Solver Configurations> Solution 1 (sol1)>Time-Dependent Solver 1** node, then click **Fully Coupled 1**.
6 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.
7 In the **Maximum number of iterations** text field, type `5`.
8 In the **Study** toolbar, click **Compute**.

Follow the instructions below to plot link motion for unloaded and loaded cases as shown in Figure 9.

RESULTS

Displacement (mbd)

In the **Model Builder** window, under **Results** right-click **Displacement (mbd)** and choose **Duplicate**.

Link Motion [Unloaded]

1 In the **Model Builder** window, under **Results** click **Displacement (mbd) 1**.
2 In the **Settings** window for **2D Plot Group**, type `Link Motion [Unloaded]` in the **Label** text field.
3 Locate the **Data** section. From the **Parameter value (para)** list, choose **0**.

Surface: All

1 In the **Model Builder** window, expand the **Link Motion [Unloaded]** node, then click **Surface**.
2 In the **Settings** window for **Surface**, type `Surface: All` in the **Label** text field.
3 Locate the **Expression** section. In the **Expression** text field, type `1`.
4 Click to expand the **Title** section. From the **Title type** list, choose **None**.
5 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.
6 From the **Color** list, choose **Gray**.

7 In the **Model Builder** window, right-click **Surface: All** and choose **Duplicate**.

Surface: Roller Plates

1 In the **Model Builder** window, under **Results>Link Motion [Unloaded]** click **Surface: All 1**.

2 In the **Settings** window for **Surface**, type `Surface: Roller Plates` in the **Label** text field.

3 Click to expand the **Title** section. Locate the **Coloring and Style** section. From the **Color** list, choose **Yellow**.

Selection 1

1 In the **Model Builder** window, expand the **Surface: Roller Plates** node.

2 Right-click **Surface: Roller Plates** and choose **Selection**.

3 In the **Settings** window for **Selection**, locate the **Selection** section.

4 From the **Selection** list, choose **Roller Plates (Roller Chain Sprocket (2D) 1)**.

Surface: Roller Plates

Right-click **Surface: Roller Plates** and choose **Duplicate**.

Surface: Link

1 In the **Model Builder** window, under **Results>Link Motion [Unloaded]** click **Surface: Roller Plates 1**.

2 In the **Settings** window for **Surface**, type `Surface: Link` in the **Label** text field.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Magenta**.

Selection 1

1 In the **Model Builder** window, expand the **Surface: Link** node, then click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 Click **Clear Selection**.

4 Select Domain 89 only.

Arrow Line 1

1 In the **Model Builder** window, right-click **Link Motion [Unloaded]** and choose **Arrow Line**.

2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.

3 In the **X-component** text field, type `mbd.u_tX`.

4 In the **Y-component** text field, type `mbd.u_tY`.

5 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `50`.

Deformation 1

1 Right-click **Arrow Line 1** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box. In the associated text field, type `1`.

Selection 1

1 In the **Model Builder** window, right-click **Arrow Line 1** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Pin Inner Boundaries (Roller Chain Sprocket (2D) 1)**.

4 In the **Link Motion [Unloaded]** toolbar, click **Plot**.

Link Motion [Unloaded]

In the **Model Builder** window, under **Results** right-click **Link Motion [Unloaded]** and choose **Duplicate**.

Link Motion [Loaded]

1 In the **Model Builder** window, under **Results** click **Link Motion [Unloaded] 1**.

2 In the **Settings** window for **2D Plot Group**, type `Link Motion [Loaded]` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (para)** list, choose **1**.

4 In the **Link Motion [Loaded]** toolbar, click **Plot**.

Follow the instructions below to plot contact force for unloaded and loaded cases as shown in Figure 10.

Contact Forces [Unloaded]

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Contact Forces [Unloaded]` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (para)** list, choose **0**.

4 Locate the **Plot Settings** section. From the **Frame** list, choose **Spatial (x, y, z)**.

Arrow Line 1

1 Right-click **Contact Forces [Unloaded]** and choose **Arrow Line**.

2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.

3 In the **X-component** text field, type `mbd.cdr1.Fnx`.

4 In the **Y-component** text field, type `mbd.cdr1.Fny`.

Deformation 1

1 Right-click **Arrow Line 1** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box. In the associated text field, type `1`.

Arrow Line 1

1 In the **Model Builder** window, click **Arrow Line 1**.

2 In the **Settings** window for **Arrow Line**, locate the **Arrow Positioning** section.

3 In the **Number of arrows** text field, type `2000`.

Line 1

1 In the **Model Builder** window, right-click **Contact Forces [Unloaded]** and choose **Line**.

2 In the **Settings** window for **Line**, locate the **Expression** section.

3 In the **Expression** text field, type `mbd.cdr1.F`.

4 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

5 Click **Change Color Table**.

6 In the **Color Table** dialog box, select **Rainbow>RainbowLight** in the tree.

7 Click **OK**.

Deformation 1

1 Right-click **Line 1** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box. In the associated text field, type `1`.

4 In the **Contact Forces [Unloaded]** toolbar, click **Plot**.

Contact Forces [Unloaded]

In the **Model Builder** window, under **Results** right-click **Contact Forces [Unloaded]** and choose **Duplicate**.

Contact Forces [Loaded]

1 In the **Model Builder** window, under **Results** click **Contact Forces [Unloaded] 1**.

2 In the **Settings** window for **2D Plot Group**, type `Contact Forces [Loaded]` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (para)** list, choose **1**.

4 In the **Contact Forces [Loaded]** toolbar, click **Plot**.

Follow the instructions below to plot link joint rotation for unloaded and loaded cases as shown in Figure 11.

Link Joint Rotation

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Link Joint Rotation` in the **Label** text field.
3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.
4 Locate the **Plot Settings** section. Select the **x-axis label** check box.
5 Select the **y-axis label** check box.
6 In the **x-axis label** text field, type `Time (s)`.
7 In the **y-axis label** text field, type `Rotation (rad)`.
8 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Global 1

1 Right-click **Link Joint Rotation** and choose **Global**.
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.cdr1hgj1.th`	`rad`	`Relative rotation`

4 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.
5 In the table, enter the following settings:

Legends
`Unloaded`
`Loaded`

Follow the instructions below to plot link joint force for unloaded and loaded cases as shown in Figure 12.

Link Joint Rotation

In the **Model Builder** window, right-click **Link Joint Rotation** and choose **Duplicate**.

Link Joint Force, Magnitude

1 In the **Model Builder** window, under **Results** click **Link Joint Rotation 1**.
2 In the **Settings** window for **1D Plot Group**, type `Link Joint Force, Magnitude` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Force [N]`.

4 Locate the **Legend** section. From the **Position** list, choose **Upper right**.

Global 1

1 In the **Model Builder** window, expand the **Link Joint Force, Magnitude** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`Flj_1`	`N`	`Link joint force, joint 1`

Follow the instructions below to plot driver and driven sprocket rotation as shown in Figure 13.

Sprocket Rotation

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Sprocket Rotation` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

4 Locate the **Plot Settings** section. Select the **x-axis label** check box.

5 Select the **y-axis label** check box.

6 In the **x-axis label** text field, type `Time (s)`.

7 In the **y-axis label** text field, type `Rotation (rad)`.

8 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Global 1

1 In the **Model Builder** window, right-click **Sprocket Rotation** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 From the **Parameter selection (para)** list, choose **First**.

5 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj1.th`	`rad`	`Relative rotation`

6 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
`Driver`

8 In the **Model Builder** window, right-click **Global 1** and choose **Duplicate**.

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Parameter selection (para)** list, choose **All**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj2.th`	`rad`	`Relative rotation`

5 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Driven (unloaded)`
`Driven (loaded)`

Follow the instructions below to plot driver and driven sprocket angular velocity as shown in Figure 14.

Sprocket Rotation

In the **Model Builder** window, right-click **Sprocket Rotation** and choose **Duplicate**.

Sprocket Angular Velocity

1 In the **Model Builder** window, under **Results** click **Sprocket Rotation 1**.

2 In the **Settings** window for **1D Plot Group**, type `Sprocket Angular Velocity` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Angular velocity (rad/s)`.

4 Locate the **Legend** section. From the **Position** list, choose **Upper right**.

Global 1

1 In the **Model Builder** window, expand the **Sprocket Angular Velocity** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj1.Tht`	`rad/s`	`Relative angular velocity`

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj2.Tht`	`rad/s`	`Relative angular velocity`

Follow the instructions below to plot driver and driven sprocket angular acceleration as shown in Figure 15.

Sprocket Angular Velocity

In the **Model Builder** window, right-click **Sprocket Angular Velocity** and choose **Duplicate**.

Sprocket Angular Acceleration

1 In the **Model Builder** window, under **Results** click **Sprocket Angular Velocity 1**.

2 In the **Settings** window for **1D Plot Group**, type `Sprocket Angular Acceleration` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Angular acceleration (rad/s^2)`.

Global 1

1 In the **Model Builder** window, expand the **Sprocket Angular Acceleration** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mbd.hgj1.Thtt`	`rad/s^2`	`Relative rotation, second time derivative`

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Time selection** list, choose **Manual**.

4 Click Range.

5 In the **Integer Range** dialog box, type 2 in the **Start** text field.

6 In the **Stop** text field, type 3001.

7 Click **Add**.

8 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

9 In the table, enter the following settings:

Expression	Unit	Description
mbd.hgj2.Thtt	rad/s^2	Relative rotation, second time derivative

Follow the instructions below to plot driver and driven sprocket angular acceleration as shown in Figure 16.

Sprocket Angular Acceleration

In the **Model Builder** window, right-click **Sprocket Angular Acceleration** and choose **Duplicate**.

Sprocket Angular Acceleration [Frequency]

1 In the **Model Builder** window, under **Results** click **Sprocket Angular Acceleration 1**.

2 In the **Settings** window for **1D Plot Group**, type Sprocket Angular Acceleration [Frequency] in the **Label** text field.

3 Locate the **Plot Settings** section. Clear the **x-axis label** check box.

4 Clear the **y-axis label** check box.

Global 1

1 In the **Model Builder** window, expand the **Sprocket Angular Acceleration [Frequency]** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Discrete Fourier transform**.

4 From the **Show** list, choose **Frequency spectrum**.

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **x-Axis Data** section.

3 From the **Parameter** list, choose **Discrete Fourier transform**.

4 From the **Show** list, choose **Frequency spectrum**.

5 In the **Sprocket Angular Acceleration [Frequency]** toolbar, click **Plot**.

Displacement

1. In the **Results** toolbar, click **Animation** and choose **Player**.
2. In the **Settings** window for **Animation**, type `Displacement` in the **Label** text field.
3. Locate the **Frames** section. In the **Number of frames** text field, type `100`.
4. Right-click **Displacement** and choose **Duplicate**.

Link Motion [Unloaded]

1. In the **Model Builder** window, click **Displacement 1**.
2. In the **Settings** window for **Animation**, type `Link Motion [Unloaded]` in the **Label** text field.
3. Locate the **Scene** section. From the **Subject** list, choose **Link Motion [Unloaded]**.
4. Right-click **Link Motion [Unloaded]** and choose **Duplicate**.

Link Motion [Loaded]

1. In the **Model Builder** window, under **Results>Export** click **Link Motion [Unloaded] 1**.
2. In the **Settings** window for **Animation**, type `Link Motion [Loaded]` in the **Label** text field.
3. Locate the **Scene** section. From the **Subject** list, choose **Link Motion [Loaded]**.
4. Right-click **Link Motion [Loaded]** and choose **Duplicate**.

Contact Forces [Unloaded]

1. In the **Model Builder** window, under **Results>Export** click **Link Motion [Loaded] 1**.
2. In the **Settings** window for **Animation**, type `Contact Forces [Unloaded]` in the **Label** text field.
3. Locate the **Scene** section. From the **Subject** list, choose **Contact Forces [Unloaded]**.
4. Click to expand the **Advanced** section. Clear the **Synchronize scales between frames** check box.
5. Right-click **Contact Forces [Unloaded]** and choose **Duplicate**.

Contact Forces [Loaded]

1. In the **Model Builder** window, under **Results>Export** click **Contact Forces [Unloaded] 1**.
2. In the **Settings** window for **Animation**, type `Contact Forces [Loaded]` in the **Label** text field.
3. Locate the **Scene** section. From the **Subject** list, choose **Contact Forces [Loaded]**.