Forces and Moments on Bevel Gears

Introduction

This model simulates a pair of straight conical bevel gears. The gears are modeled as rigid. A transient analysis is performed to compute the forces and moments at the center of the fixed gear. This model is built using the gears functionality in the Multibody Dynamics interface in COMSOL Multiphysics.

The data for this model is taken from Ref. 1. The results of the analysis are compared with the results given in the reference.

Model Definition

The model geometry is shown in Figure 1. It has three components: wheel, pinion, and a rigid bar. Both the wheel and pinion are modeled as bevel gears. The wheel is fixed on its location. The pinion is mounted on a rigid bar through a hinge joint. The rigid bar is hinged at a point lying on the axis of the wheel.

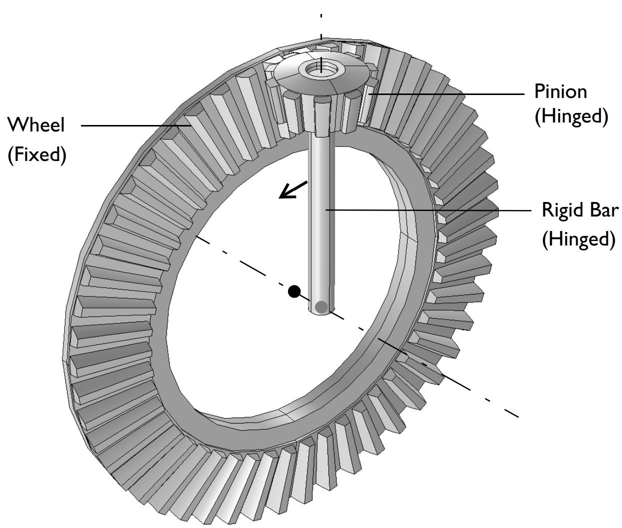

Figure 1: Model geometry. The wheel center, the hinge location of rigid bar, and the axis of both the gears are also shown.

MODEL PARAMETERS

The properties of the wheel and pinion are given in the table below:

TABLE 1: GEAR PROPERTIES

PROPERTIES		WHEEL	PINION
Number of teeth	n	50	10
Pitch diameter	d_p	100 mm	20 mm
Pressure angle	α	20°	20°
Cone angle	γ	78.7°	11.3°
Center of rotation	$\mathbf{x}_c$	(0, 0, 0) mm	(0, -10, 50) mm
Axis of rotation	$\mathbf{e}_g$	(0, -1, 0)	(0, 0, -1)

The pinion is hinged to the rigid bar about the its own axis. The rigid bar is hinged to the ground about the wheel axis. The center of this hinge joint is $(0, 10\text{ mm}, 0)$.

CONSTRAINTS AND LOADS

- The wheel is fixed to the ground.
- The rigid bar is given a rotation of 1 rad.
- A resisting torque of 10 N·m is applied at the joint between pinion and the rigid bar.

Results and Discussion

The comparison of the computed results with the solution presented in Ref. 1 is given in the tables below:

TABLE 2: CONTACT FORCE AND REACTION FORCES

	FC	FX	FY	FZ
Computed values (in N)	1064.2	600.32	356.92	802.94
Reference values (in N)	1064	600.35	356.9	802.9

TABLE 3: REACTION MOMENTS

	MX	MY	MZ
Computed values (in N·m)	-9.642	50	-15.017
Reference values (in N·m)	-9.641	50	-15.016

It can be seen that the computed values of the forces and moments are in the very close agreement with the reference values. The units and the coordinate system are different in the reference model. Hence reference results are adjusted appropriately before using them for the comparison.

Figure 2 shows the position of the pinion and the rigid bar after 1 rad of rotation.

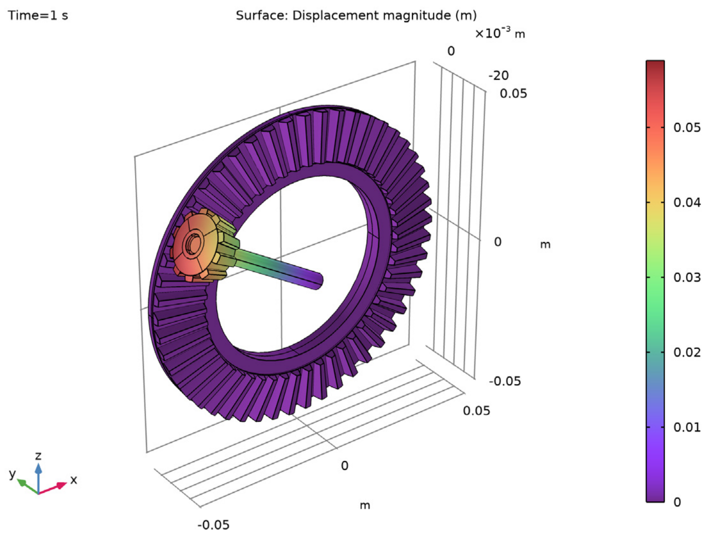

Figure 2: Displacement of the pinion and the rigid bar after 1 rad of rotation.

Figure 3 and Figure 4 show the reaction forces and moments at the wheel center. The forces and moments are plotted for various positions of the pinion.

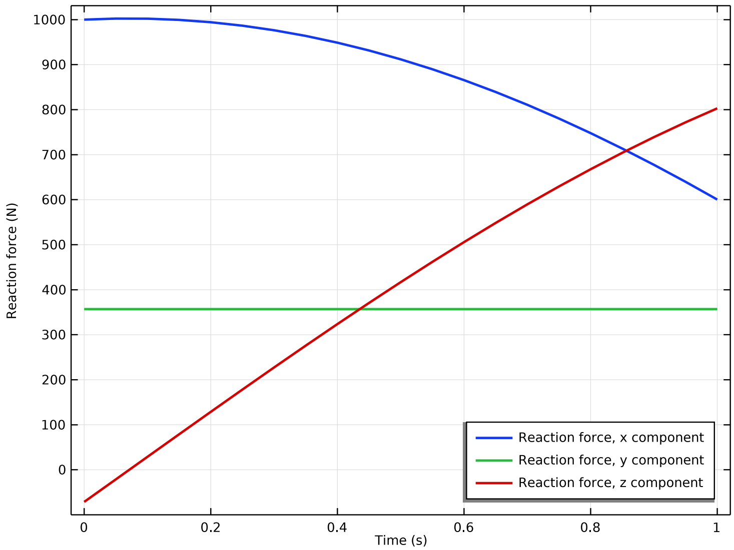

Figure 3: Reaction forces at the center of the wheel.

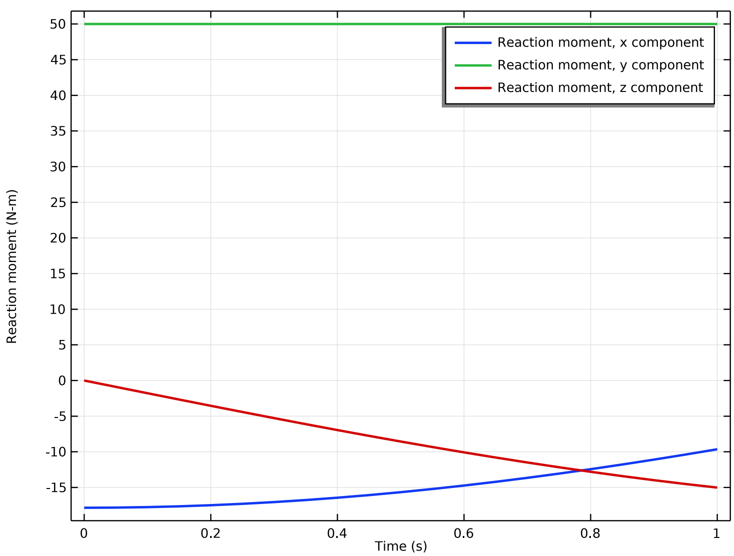

Figure 4: Reaction moments at the center of the wheel.

Notes About the COMSOL Implementation

- To build a gear geometry, you can import a gear part from the **Parts Library** and customize it by changing its input parameters. Alternatively, you can also create an equivalent disc or cone to represent the gear.
- All the gears are assumed rigid. The elasticity of a gear mesh can be included on **Gear Pair** nodes using the **Gear Elasticity** subnode.
- All the **Gear Pair** nodes are assumed ideal and frictionless. You can add **Transmission Error**, **Backlash**, or **Friction** subnodes when required.
- To constraint the motion of a gear, you can use **Prescribed Displacement/Rotation** or **Fixed Constraint** subnodes. Alternatively, you can mount the gears on a shaft or on the ground through various **Joint** nodes.
- The contact force on a **Gear Pair** is computed using **Weak constraints** or **Penalty method**. By default, the contact force computation is turned off. Use the weak constraints method for more accurate contact forces; however, you can, preferably, switch to the penalty method for large rigid body systems.

References

1. A. Cardona, "Three-Dimensional Gears Modeling in Multibody Systems Analysis," *International Journal for Numerical Methods in Engineering*, vol. 40, pp. 357–381, 1997.

Application Library path: `Multibody_Dynamics_Module/Verification_Examples/bevel_gear_pair`

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 **3D**.

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 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `bevel_gear_pair_parameters.txt`.

PART LIBRARIES

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

2 In the **Part Libraries** window, select **Multibody Dynamics Module>3D>External Gears>bevel_gear** in the tree.

3 Click **Add to Geometry**.

GEOMETRY 1

Bevel Gear 1 (pi1)

1 In the **Home** toolbar, click **Build All**.

To customize the gear geometry, enter the gear parameters in the input parameters of the part.

2 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Bevel Gear 1 (pi1)**.

3 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.

4 In the table, enter the following settings:

Name	Expression	Value	Description
n	n1	50	Number of teeth
dp	dp1	0.1 m	Pitch diameter
alpha	alpha	20 °	Pressure angle
gamma	gamma1	78.7 °	Cone angle

Name	Expression	Value	Description
adr	0.75	0.75	Addendum to module ratio
tfr	0	0	Tip fillet radius to pitch diameter ratio (Set 0 for no fillet)
rfr	0	0	Root fillet radius to pitch diameter ratio (Set 0 for no fillet)
dhr	0.6	0.6	Hole diameter to pitch diameter ratio (Set 0 for no hole)
wgr	0.03	0.03	Gear width to pitch diameter ratio
lsr	0	0	Shaft length to pitch diameter ratio (Set 0 for no shaft)
xc	xcx1	0 m	Gear center, x coordinate
yc	xcy1	0 m	Gear center, y coordinate
zc	xcz1	0 m	Gear center, z coordinate
egx	ex1	0	Gear axis, x component
egy	ey1	-1	Gear axis, y component
egz	ez1	0	Gear axis, z component

Bevel Gear 2 (pi2)

1 In the **Geometry** toolbar, click **Parts** and choose **Bevel Gear**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
n	n2	10	Number of teeth
dp	dp2	0.02 m	Pitch diameter
alpha	alpha	20 °	Pressure angle
gamma	gamma2	11.3 °	Cone angle
adr	0.3	0.3	Addendum to module ratio
htr	3	3	Tooth height to addendum ratio
tfr	0	0	Tip fillet radius to pitch diameter ratio (Set 0 for no fillet)
rfr	0	0	Root fillet radius to pitch diameter ratio (Set 0 for no fillet)

Name	Expression	Value	Description
wgr	0.4	0.4	Gear width to pitch diameter ratio
wbr	0.1	0.1	Back cone width to gear width ratio
wcr	0	0	Collar width to gear width ratio (Set 0 for no collar)
lsr	0	0	Shaft length to pitch diameter ratio (Set 0 for no shaft)
xc	xcx2	0 m	Gear center, x coordinate
yc	xcy2	-0.01 m	Gear center, y coordinate
zc	xcz2	0.05 m	Gear center, z coordinate
egx	ex2	0	Gear axis, x component
egy	ey2	0	Gear axis, y component
egz	ez2	-1	Gear axis, z component
th	360/(2*n2)[deg]	18 °	Mesh alignment angle

Cylinder 1 (cyl1)

1 In the **Geometry** toolbar, click **Cylinder**.

2 In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.

3 In the **Radius** text field, type dp2/8.

4 In the **Height** text field, type dp1/2.

5 Locate the **Position** section. In the **x** text field, type xcx2.

6 In the **y** text field, type xcy2.

7 In the **z** text field, type xcz2.

8 Locate the **Axis** section. From the **Axis type** list, choose **Cartesian**.

9 In the **z** text field, type -1.

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 In the **Geometry** toolbar, click **Build All**.

MULTIBODY DYNAMICS (MBD)

Add two **Bevel Gear** nodes and specify all the properties of gears. For the automated creation of **Bevel Gear** nodes from geometry parts, use **Automated Model Setup** section of Multibody Dynamics node.

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

2 In the **Settings** window for **Multibody Dynamics**, click **Physics Node Generation** in the upper-right corner of the **Automated Model Setup** section. From the menu, choose **Create Gears**.

Bevel Gear 1

1 In the **Model Builder** window, expand the **Gears** node, then click **Bevel Gear 1**.

2 In the **Settings** window for **Bevel Gear**, locate the **Density** section.

3 From the ρ list, choose **User defined**.

Fixed Constraint 1

1 In the **Physics** toolbar, click **Attributes** and choose **Fixed Constraint**.

2 In the **Settings** window for **Fixed Constraint**, click to expand the **Reaction Force Settings** section.

3 Select the **Evaluate reaction forces** check box.

Bevel Gear 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)>Gears** click **Bevel Gear 2**.

2 In the **Settings** window for **Bevel Gear**, locate the **Density** section.

3 From the ρ list, choose **User defined**.

Now add a **Gear Pair** node to connect the two bevel gears.

Gear Pair 1

1 In the **Physics** toolbar, click **Global** and choose **Gear Pair**.

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

3 From the **Wheel** list, choose **Bevel Gear 1**.

4 From the **Pinion** list, choose **Bevel Gear 2**.

5 Locate the **Contact Force Computation** section. From the list, choose **Computed using weak constraints**.

Rigid Material: Bar

1 In the **Physics** toolbar, click **Domains** and choose **Rigid Material**.

2 Select Domain 5 only.

3 In the **Settings** window for **Rigid Material**, type `Rigid Material: Bar` in the **Label** text field.

4 Locate the **Density** section. From the ρ list, choose **User defined**.

Hinge Joint 1

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

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

3 From the **Source** list, choose **Rigid Material: Bar**.

4 From the **Destination** list, choose **Bevel Gear 2**.

5 Locate the **Center of Joint** section. From the list, choose **Centroid of selected entities**.

6 From the **Entity level** list, choose **Point**.

Center of Joint: Point 1

1 In the **Model Builder** window, click **Center of Joint: Point 1**.

2 In the **Settings** window for **Center of Joint: Point**, locate the **Point Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `648, 650` in the **Selection** text field.

5 Click **OK**.

Hinge Joint 1

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

2 In the **Settings** window for **Hinge Joint**, locate the **Axis of Joint** section.

3 Specify the $\mathbf{e}_0$ vector as

0	x
0	y
1	z

Apply an external torque on this joint.

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 `M_b`.

Hinge Joint 2

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

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

3 From the **Source** list, choose **Fixed**.

4 From the **Destination** list, choose **Rigid Material: Bar**.

5 Locate the **Center of Joint** section. From the **Entity level** list, choose **Point**.

Center of Joint: Point 1

1 In the **Model Builder** window, click **Center of Joint: Point 1**.

2 In the **Settings** window for **Center of Joint: Point**, locate the **Point Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `647, 649` in the **Selection** text field.

5 Click **OK**.

Hinge Joint 2

1 In the **Model Builder** window, click **Hinge Joint 2**.

2 In the **Settings** window for **Hinge Joint**, locate the **Axis of Joint** section.

3 Specify the $\mathbf{e}_0$ vector as

0	x
1	y
0	z

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 In the θ_p text field, type `-th_b*t[1/s]`.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Fine**.

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(0,0.05,1)`.

4 In the **Home** toolbar, click **Compute**.

RESULTS

Displacement (mbd)

1 In the **Displacement (mbd)** toolbar, click **Plot**.

2 Click the **Zoom Extents** button in the **Graphics** toolbar.

Evaluate the contact force, reaction force, and the reaction moment at the center of the fixed bevel gear.

Global Evaluation 1

1 In the **Results** toolbar, click **Global Evaluation**.

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

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

4 Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Gear pairs>Gear Pair 1> mbd.grp1.Fc - Force at contact point - N**.

5 Click **Evaluate**.

Global Evaluation 2

1 In the **Results** toolbar, click **Global Evaluation**.

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

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

4 Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1> Reaction force - N>mbd.bvg1.RFx - Reaction force, x component**.

5 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1> Reaction force - N>mbd.bvg1.RFy - Reaction force, y component**.

6 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction force - N>mbd.bvg1.RFz - Reaction force, z component**.

7 Click ▾ next to **Evaluate**, then choose **New Table**.

Global Evaluation 3

1 In the **Results** toolbar, click **Global Evaluation**.

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

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

4 Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction moment - N·m>mbd.bvg1.RMx - Reaction moment, x component**.

5 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction moment - N·m>mbd.bvg1.RMy - Reaction moment, y component**.

6 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction moment - N·m>mbd.bvg1.RMz - Reaction moment, z component**.

7 Click ▾ next to **Evaluate**, then choose **New Table**.

Use the following instructions to plot the time variation of reaction forces and reaction moments as shown in Figure 3 and Figure 4 respectively.

Reaction forces

1 In the **Results** toolbar, click **1D Plot Group**.

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

Global 1

1 Right-click **Reaction forces** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction force - N>mbd.bvg1.RFx - Reaction force, x component**.

3 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction force - N>mbd.bvg1.RFy - Reaction force, y component**.

4 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1> Reaction force - N>mbd.bvg1.RFz - Reaction force, z component**.

5 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

Reaction forces

1 In the **Model Builder** window, click **Reaction forces**.

2 In the **Settings** window for **1D Plot Group**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section.

5 Select the **y-axis label** check box. In the associated text field, type `Reaction force (N)`.

6 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

7 In the **Reaction forces** toolbar, click **Plot**.

8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Reaction moments

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

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

Global 1

1 Right-click **Reaction moments** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Multibody Dynamics>Bevel gears>Bevel Gear 1>Reaction moment - N·m>mbd.bvg1.RMx - Reaction moment, x component**.

3 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1> Reaction moment - N·m>mbd.bvg1.RMy - Reaction moment, y component**.

4 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Multibody Dynamics>Bevel gears>Bevel Gear 1> Reaction moment - N·m>mbd.bvg1.RMz - Reaction moment, z component**.

5 Locate the **Coloring and Style** section. From the **Width** list, choose **2**.

Reaction moments

1 In the **Model Builder** window, click **Reaction moments**.

2 In the **Settings** window for **1D Plot Group**, locate the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section.

5 Select the **y-axis label** check box. In the associated text field, type `Reaction moment (N-m)`.

6 In the **Reaction moments** toolbar, click **Plot**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.

Modify the default velocity plot to show the gears and use it to create an animation.

Gears

1 In the **Model Builder** window, expand the **Results>Velocity (mbd)** node, then click **Velocity (mbd)**.

2 In the **Settings** window for **3D Plot Group**, type `Gears` in the **Label** text field.

Arrow Line

1 In the **Model Builder** window, under **Results>Gears** right-click **Arrow Line** and choose **Delete**.

2 Click **Yes** to confirm.

Volume

1 In the **Model Builder** window, under **Results>Gears** click **Volume**.

2 In the **Settings** window for **Volume**, locate the **Coloring and Style** section.

3 Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Aurora>AuroraAustralis** in the tree.

5 Click **OK**.

Volume

1 In the **Model Builder** window, click **Volume**.

2 In the **Gears** toolbar, click **Plot**.

Animation 1

1 In the **Results** toolbar, click **Animation** and choose **Player**.

2 In the **Settings** window for **Animation**, locate the **Scene** section.

3 From the **Subject** list, choose **Gears**.