Created in COMSOL Multiphysics 6.2

Andrew’s Squeezing Mechanism

Introduction

This model simulates the dynamic behavior of Andrew's squeezing mechanism. This is a benchmark problem for testing the numerical algorithms in the area of multibody dynamics. It requires small time steps due to a very short time scale of the problem.

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 geometry of the Andrew's mechanism is shown in Figure 1. The geometry consists of seven links interconnected by ten hinge joints. This mechanism is also known as the *seven body mechanism*.

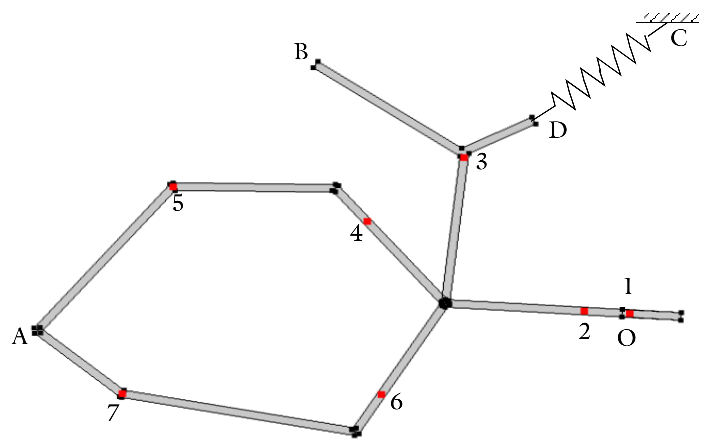

Figure 1: Model geometry (the center of mass of each link is highlighted).

The links of the mechanism are assumed to be rigid bodies. The mechanism is fixed at four points: O, A, B, and C. The center of mass of each link is shown in Figure 1, and the mass and moment of inertia of each link about its center of mass are given in the Table 1.

TABLE 1: MASS AND MOMENT OF INERTIA OF LINKAGES.

Linkage	**Mass (kg)**	**Moment of Inertia (kg·m^2)**
1	0.04325	2.194e-6
2	0.00365	4.410e-7
3	0.02373	5.255e-6
4	0.00706	5.667e-7
5	0.07050	1.169e-5
6	0.00706	5.667e-7
7	0.05498	1.912e-5

The initial values of the angles in the mechanism are given in Table 2. The details about these angles can be obtained in Ref. 2.

TABLE 2: INITIAL VALUES OF THE ANGLES IN ANDREW'S MECHANISM.

Angle	**Value (rad)**
beta0	-0.0620
theta0	0
gamma0	0.4552
delta0	0.4873
phi0	0.2227
omega0	0.2227
epsilon0	1.2305

Gravity is neglected, and the mechanism is initially at rest. A spring of stiffness c_0 = 4530 N/m is attached between point C and point D with an initial length of l_0 = 0.07785 m. A moment M_0 = 0.033 Nm is prescribed on the right crank, link 1.

Results and Discussion

The computed results are compared with the solution presented in Ref. 1. The computed results are in a very good agreement with the results given in the reference. Figure 2 shows the displacement of the mechanism at $t = 0.028$ s.

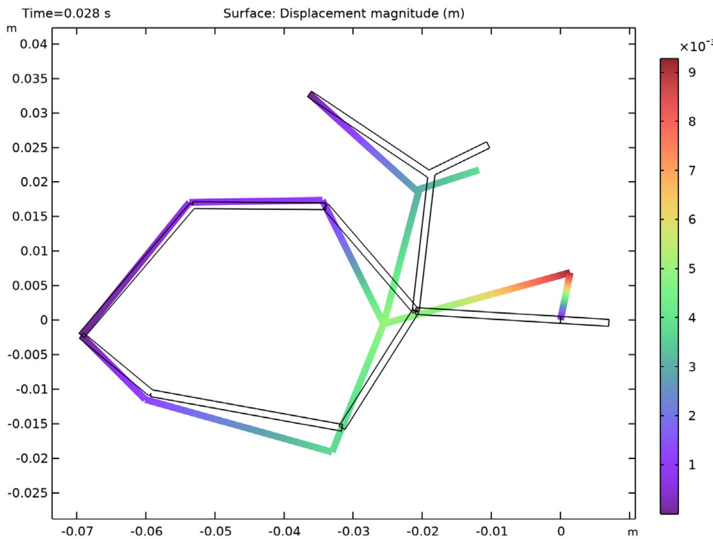

Figure 2: Motion of linkages in Andrew's mechanism at a particular instant.

Figure 3 displays the time variation of the angles between different links in the Andrew's mechanism. The computed angles are the function of relative rotations on the hinge joints. The computed angles, shown with solid lines, are in very good agreement with the results given in Ref. 1.

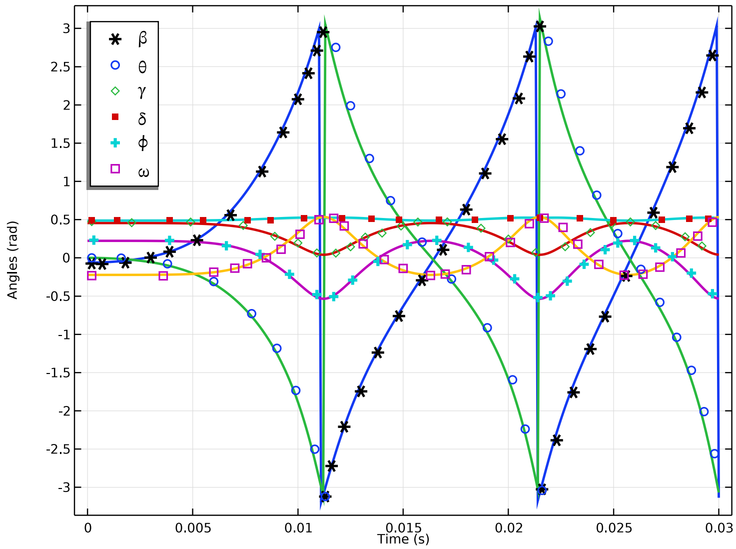

Figure 3: Comparison of time variation of angles in Andrew's mechanism with Ref. 1. *The results obtained in COMSOL are shown with solid lines.*

Notes About the COMSOL Implementation

- In this model, linkages are modeled as rigid elements using the **Rigid Material** node as we are only interested in the kinematics of the mechanism. Linkages can be modeled as flexible elements using the **Linear Elastic Material** node if the stresses and deformations in the linkages are also of interest.
- The **Mass and Moment of Inertia** subnode of the **Rigid Material** is used to enter the inertia properties given at a certain point.
- A **Joint** node can establish a connection between a **Rigid Material** or an **Attachment** node with the ground (**Fixed**). This helps in avoiding extra geometry components.
- The **Spring-Damper** node is used to connect points C and D with an elastic spring.
- The connections set up in the model can be reviewed in the **Joints Summary** section at the physics interface node.
- The net degrees of freedom of this system can be seen in the **Rigid Body DOF Summary** section at the physics interface node.

References

1. J. Cuadrado, J. Cardenal, and E. Bayo, “Modeling and Solution Methods for Efficient Real-Time Simulation of Multibody Dynamics,” *Multibody System Dynamics*, vol. 1, pp. 259–280, 1997.

2. W. Schiehlen, *Multibody Systems Handbook*, Springer-Verlag Berlin Heidelberg, 1990.

Application Library path: `Multibody_Dynamics_Module/Verification_Examples/andrews_mechanism`

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**.

GEOMETRY 1

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.

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

3 Click **Browse**.

4 Browse to the model’s Application Libraries folder and double-click the file `andrews_mechanism.mphbin`.

5 Click **Import**.

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

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

GLOBAL DEFINITIONS

Import the inertia properties of all the linkages.

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 `andrews_mechanism_parameters.txt`.

MULTIBODY DYNAMICS (MBD)

Rigid Material 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Multibody Dynamics (mbd)** and choose **Material Models>Rigid Material**.

2 Select Domain 7 only.

Set the density of the selected rigid domain to zero. Use a Mass and Moment of Inertia subnode instead to specify the mass, moment of inertia, and center of mass of the domain.

3 In the **Settings** window for **Rigid Material**, locate the **Density** section.

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

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 **Center of Mass** section.

3 From the list, choose **Centroid of selected entities**.

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

5 Locate the **Mass and Moment of Inertia** section. In the m text field, type `m1`.

6 In the I_z text field, type `I1`.

Center of Mass: Point 1

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

2 Select Point 44 only.

Rigid Materials

Similarly, create other rigid domains by duplicating **Rigid Material 1** and resetting the inputs using the information given in the table below:

Name	**Selection**	**Mass**	**Moment of Inertia**	**Center of Mass (Point)**
Rigid Material 2	6	m2	I2	39
Rigid Material 3	3	m3	I3	23
Rigid Material 4	4	m4	I4	29
Rigid Material 5	1	m5	I5	4
Rigid Material 6	5	m6	I6	34
Rigid Material 7	2	m7	I7	13

Apply the moment on the crank using an **Applied Moment** subnode of the rigid material.

Rigid Material 1

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

Applied Moment 1

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

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

3 In the M_z text field, type `M0`.

Rigid Material 1, Rigid Material 2, Rigid Material 3, Rigid Material 4, Rigid Material 5, Rigid Material 6, Rigid Material 7

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Rigid Material 1**, **Rigid Material 2**, **Rigid Material 3**, **Rigid Material 4**, **Rigid Material 5**, **Rigid Material 6**, and **Rigid Material 7**.

2 Right-click and choose **Group**.

Rigid Materials

In the **Settings** window for **Group**, type `Rigid Materials` in the **Label** text field.

Model the spring connection using a Spring-Damper node.

Spring–Damper 1

1 In the **Physics** toolbar, click **Global** and choose **Spring–Damper**.

2 In the **Settings** window for **Spring–Damper**, locate the **Attachment Selection** section.

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

4 Specify the $\mathbf{X}_s$ vector as

xC	x
yC	y

5 From the **Destination** list, choose **Rigid Material 3**.

6 From the **Connection point** list, choose **Centroid of selected entities**.

Destination Point: Boundary 1

1 In the **Model Builder** window, click **Destination Point: Boundary 1**.

2 Select Boundary 25 only.

Spring–Damper 1

1 In the **Model Builder** window, click **Spring–Damper 1**.

2 In the **Settings** window for **Spring–Damper**, locate the **Spring–Damper** section.

3 In the k text field, type `c0`.

4 Click to expand the **Free Length** section. From the list, choose **Specify free length**.

5 In the l_f text field, type `10`.

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 **Fixed**.

4 From the **Destination** list, choose **Rigid Material 1**.

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 Select Points 42 and 43 only.

Hinge Joints

Create more joints by duplicating **Hinge Joint 1** and resetting the inputs using the information given in the table below:

Name	Source	Destination	Center of Joints (points)
Hinge Joint 2	Rigid Material 1	Rigid Material 2	`45, 46`
Hinge Joint 3	Rigid Material 2	Rigid Material 3	`37, 38`
Hinge Joint 4	Rigid Material 2	Rigid Material 4	`37, 38`
Hinge Joint 5	Rigid Material 2	Rigid Material 6	`37, 38`
Hinge Joint 6	Rigid Material 5	Rigid Material 4	`27, 28`
Hinge Joint 7	Rigid Material 7	Rigid Material 6	`32, 33`
Hinge Joint 8	Fixed	Rigid Material 5	`1, 2`
Hinge Joint 9	Fixed	Rigid Material 7	`9, 10`
Hinge Joint 10	Fixed	Rigid Material 3	`17, 18`

Hinge Joint 1, Hinge Joint 10, Hinge Joint 2, Hinge Joint 3, Hinge Joint 4, Hinge Joint 5, Hinge Joint 6, Hinge Joint 7, Hinge Joint 8, Hinge Joint 9

1 In the **Model Builder** window, under **Component 1 (comp1)>Multibody Dynamics (mbd)**, Ctrl-click to select **Hinge Joint 1**, **Hinge Joint 2**, **Hinge Joint 3**, **Hinge Joint 4**, **Hinge Joint 5**, **Hinge Joint 6**, **Hinge Joint 7**, **Hinge Joint 8**, **Hinge Joint 9**, and **Hinge Joint 10**.

2 Right-click and choose **Group**.

Hinge Joints

In the **Settings** window for **Group**, type `Hinge Joints` in the **Label** text field.

DEFINITIONS

Create the following variables for use in the postprocessing.

Some of the angles of the mechanism are modified using the modulus operator in order to obtain the representation used in Ref. 1.

Variables 1

1 In the **Home** toolbar, click a= **Variables** and choose **Local Variables**.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
beta	mod(mbd.hgj1.th-pi,2*pi)-pi+beta0	rad	beta
theta	mod(mbd.hgj2.th-pi,2*pi)-pi+theta0	rad	theta
gamma	mbd.hgj10.th+gamma0	rad	gamma
delta	mbd.hgj8.th+delta0	rad	delta
phi	mbd.hgj6.th+phi0	rad	phi
omega	mbd.hgj7.th-omega0	rad	omega

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-4,0.03).

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

RESULTS

Displacement (mbd)

The two default plots show the displacement and velocity profile of the Andrew's mechanism. The first default plot is shown in Figure 2.

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

2 From the **Frame** list, choose **Material (X, Y, Z)**.

3 Locate the **Data** section. From the **Time (s)** list, choose **0.028**.

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

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

Import the following tables, containing the results obtained in Ref. 1, for comparison.

beta

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type beta in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

theta

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type `theta` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

gamma

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type `gamma` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

delta

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type `delta` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

phi

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type `phi` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

omega

1 In the **Results** toolbar, click **Table**.

2 In the **Settings** window for **Table**, type `omega` in the **Label** text field.

3 Locate the **Data** section. Click **Import**.

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

Use the following instructions to plot the time variation of the angles in the mechanism shown in Figure 3.

Angles

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

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

Global 1

1 Right-click **Angles** 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)>Definitions>Variables>beta - beta - rad**.

3 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>theta - theta - rad**.

4 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>gamma - gamma - rad**.

5 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>delta - delta - rad**.

6 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>phi - phi - rad**.

7 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>omega - omega - rad**.

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

9 Click to expand the **Legends** section. Clear the **Show legends** check box.

Table Graph 1

1 In the **Model Builder** window, right-click **Angles** and choose **Table Graph**.

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

3 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

4 Find the **Line style** subsection. From the **Line** list, choose **None**.

5 Click to expand the **Legends** section. Select the **Show legends** check box.

6 From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
`\beta`

8 Right-click **Table Graph 1** and choose **Duplicate**.

Table Graph 2

1 In the **Model Builder** window, click **Table Graph 2**.

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

3 From the **Table** list, choose **theta**.

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

Legends
`\theta`

5 Right-click **Table Graph 2** and choose **Duplicate**.

Table Graph 3

1 In the **Model Builder** window, click **Table Graph 3**.

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

3 From the **Table** list, choose **gamma**.

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

Legends
`\gamma`

5 Right-click **Table Graph 3** and choose **Duplicate**.

Table Graph 4

1 In the **Model Builder** window, click **Table Graph 4**.

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

3 From the **Table** list, choose **delta**.

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

Legends
`\delta`

5 Right-click **Table Graph 4** and choose **Duplicate**.

Table Graph 5

1 In the **Model Builder** window, click **Table Graph 5**.

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

3 From the **Table** list, choose **phi**.

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

Legends
`\phi`

5 Right-click **Table Graph 5** and choose **Duplicate**.

Table Graph 6

1 In the **Model Builder** window, click **Table Graph 6**.

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

3 From the **Table** list, choose **omega**.

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

Legends
`\omega`

Angles

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

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

3 From the **Position** list, choose **Upper left**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Plot Settings** section.

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

7 Select the **y-axis label** check box. In the associated text field, type `Angles (rad)`.

8 In the **Angles** toolbar, click **Plot**.

Finally, to generate an animation of Andrew's mechanism, follow these instructions:

Animation 1

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

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

3 In the **Number of frames** text field, type `100`.