



Model created in COMSOL Multiphysics 6.4

Andrew's Squeezing Mechanism

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 ($\text{kg}\cdot\text{m}^2$)
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 $c_0 = 4530 \text{ N/m}$ is attached between point C and point D with an initial length of $l_0 = 0.07785 \text{ m}$. A moment $M_0 = 0.033 \text{ Nm}$ 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.

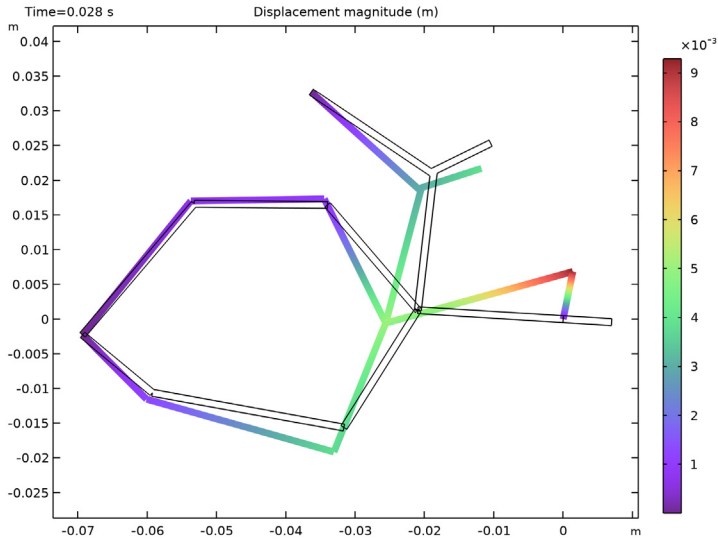


Figure 2: Motion of linkages in Andrew's mechanism at a particular instant.

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.

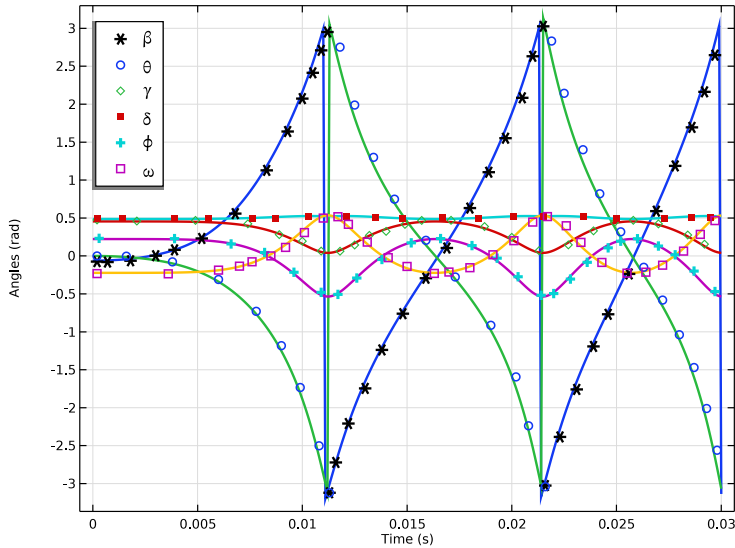


Figure 3: Comparison of time variation of angles in Andrew's mechanism with Ref. 1. The results obtained in COMSOL are shown with solid lines.

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.
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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 I

Import 1 (imp1)

- 1 In the **Home** toolbar, click  **Import**.
- 2 In the **Settings** window for **Import**, locate the **Source** 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 **Physics** toolbar, click  **Domains** and choose **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** 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 **Definitions** toolbar, click $\alpha =$ **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	$\text{mod}(\text{mbd.hgj1.th}-\pi, 2*\pi) - \pi + \text{beta0}$	rad	beta
theta	$\text{mod}(\text{mbd.hgj2.th}-\pi, 2*\pi) - \pi + \text{theta0}$	rad	theta
gamma	$\text{mbd.hgj10.th} + \text{gamma0}$	rad	gamma
delta	$\text{mbd.hgj8.th} + \text{delta0}$	rad	delta
phi	$\text{mbd.hgj6.th} + \text{phi0}$	rad	phi
omega	$\text{mbd.hgj7.th} - \text{omega0}$	rad	omega

STUDY I



Step 1: Time Dependent

- 1 In the **Model Builder** window, under **Study I** 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 **Study** 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  **ID Plot Group**.
- 2 In the **Settings** window for **ID 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** checkbox.

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** checkbox.
- 6 From the **Legends** list, choose **Manual**.
- 7 In the table, enter the following settings:

Legends

\beta

Table Graph 2

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

- 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

θ

Table Graph 3

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

γ

Table Graph 4

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

δ

Table Graph 5

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

ϕ

Table Graph 6


- 1 Right-click **Table Graph 5** and choose **Duplicate**.
- 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 **ID 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** checkbox. In the associated text field, type **Time (s)**.
- 7 Select the **y-axis label** checkbox. 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.