Model created in COMSOL Multiphysics 6.4

Response of a Rotor Under the Influence of Seal Forces

Introduction

In fluid seals found in axial compressors, two types of fluid forces can be distinguished. The first type of force directly opposes the lateral motion of the rotor, and it is modeled using equivalent direct stiffness and damping coefficients. The second force type acts in the circumferential direction of the rotor. This force is modeled with cross stiffness and damping coefficients. The first type of force always tends to stabilize the rotor, whereas the second type may have destabilizing effects under certain conditions.

In this example, an axial compressor is modeled using the Beam Rotor interface. The compressor has ten impeller stages with a seal located near each impeller. The compressor model also includes a balance piston seal located at the end of all impeller stages. The time-dependent response of the compressor is studied for a gradually increasing rotor speed. In order to compare the effect of the seals on the rotor response, two studies are performed, one without seals and one with the seals included. In this case, the seals have a stabilizing effect on the compressor as the displacement amplitude is significantly smaller in the presence of the seals.

Model Definition

The model consists of an axial compressor with ten impeller stages. The overall configuration is shown in Figure 1. The rotor is supported with two hydrodynamic bearings. Each impeller stage is accompanied by a seal to avoid flow leakage. In addition, there is a balance piston seal at the end of the impeller stages. The rotor is supported by the bearings and the seals. The impellers are modeled with small mass eccentricities.

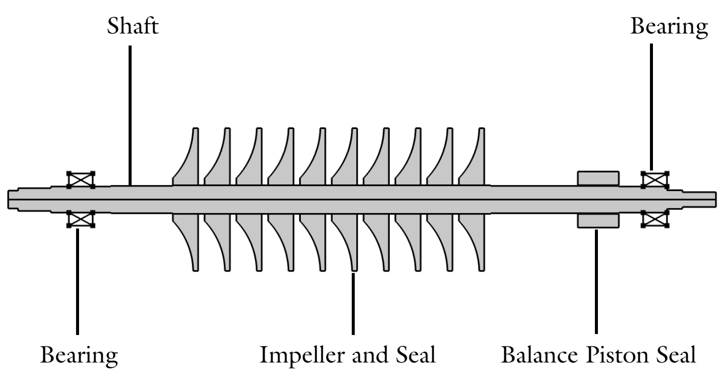

Figure 1: Rotor geometry.

SHAFT PROPERTIES

The diameter of the rotor shaft varies along its length. Thus, to more easily apply different properties, the rotor axis is divided into multiple segments separated by various support points. Some of these points separate segments with different shaft diameters; others mark the locations of seals, impellers, and bearings. The coordinates of the various stations are given in Table 1.

TABLE 1: STATION COORDINATES.

STATION	COORDINATE
1	0
2	0.04 m
3	0.172 m
4	0.413 m
5	0.663 m
6	1.943 m
7	2.459 m
8	2.653 m
9	2.715 m
10	2.850 m

The shaft diameters for the different segments are given in the Table 2.

TABLE 2: SHAFT DIAMETERS.

SHAFT SEGMENT	DIAMETER
Station 1–2	72 mm
Station 2–3	92 mm
Station 3–4	105 mm
Station 4–5	110 mm
Station 5–6	115 mm
Station 6–7	110 mm
Station 7–8	105 mm
Station 8–9	75 mm
Station 9–10	60 mm

IMPELLER PROPERTIES

The properties of the impellers are given in the Table 3.

TABLE 3: IMPELLER PROPERTIES.

IMPELLER	MASS	DIAMETRAL MOMENT OF INERTIA	POLAR MOMENT OF INERTIA	ECCENTRICITY
1	15 kg	0.131 $kg{\cdot}m^2$	0.262 $kg{\cdot}m^2$	0.01 mm
2–9	13 kg	0.114 $kg{\cdot}m^2$	0.228 $kg{\cdot}m^2$	0.01 mm
10	14 kg	0.122 $kg{\cdot}m^2$	0.244 $kg{\cdot}m^2$	0.01 mm

All impellers are located between stations 5 and 6, and they are equidistantly spaced in this shaft segment. The first impeller is located at a distance of 62 mm from station 5. The axial length of each impeller is 80 mm.

BEARING PROPERTIES

The rotor is supported on two plain hydrodynamic journal bearings. The first bearing is located in the middle of stations 3 and 4. The second bearing is located adjacent to station 8 such that the right end of the bearing touches this station. The length of each bearings is 96 mm. The radius of both bearings is 52.5 mm and the radial clearance in each bearing is 0.15 mm. The viscosity of the bearing lubricant is 0.0414 Pa·s.

SEAL PROPERTIES

The properties of the seals are given in the Table 4.

TABLE 4: SEAL PROPERTIES.

SEAL	DIAMETER	CLEARANCE	LENGTH	PRESSURE DROP
Annular seals 1–10	195 mm	0.5 mm	22 mm	3.2 MPa
Balance piston seal	80 mm	0.5 mm	165 mm	32 MPa

The annular seals are equidistantly spaced between stations 5 and 6 on the rotor with the left end of the first seal starting at station 5. The right end of the balance piston seal is located at station 7. The density and viscosity of the seal fluid are 800 kg/m^3 and 0.02 Pa·s, respectively.

Results and Discussion

Figure 2 shows the von Mises stress in the rotor after including the seal forces at t = 2 seconds. The response appears to be similar to the first bending mode of the rotor. The rotor geometry is also shown below the stress plot.

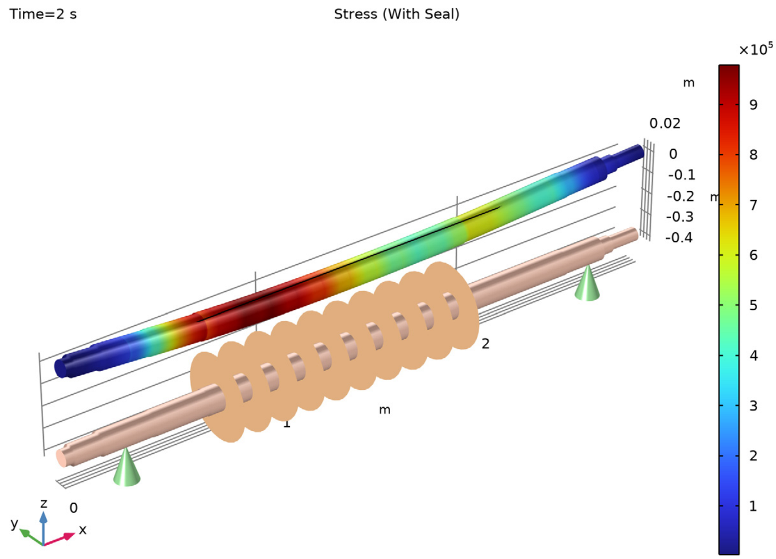

Figure 2: The von Mises stress in the rotor with seals at t = 2 seconds.

The orbit of the rotor near the left bearing is shown in Figure 3. In the presence of seals, the displacement amplitude of the whirl is considerably smaller. The orbit plot indicates a growing whirl amplitude in the absence of seals toward the end of the simulation.

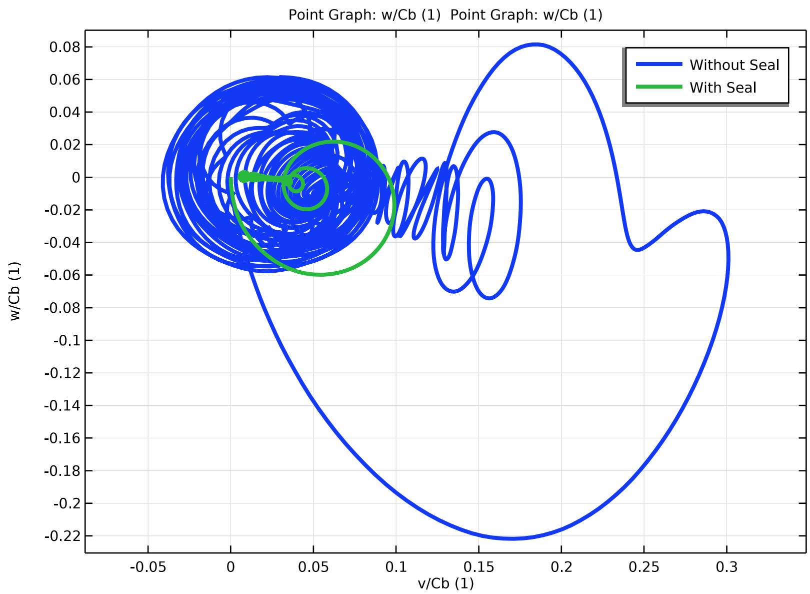

Figure 3: Orbit of the rotor in the bearing with and without seals.

The stiffness and damping coefficients of seals play an important role in dictating the rotor stability. The direct and cross stiffnesses for the balance piston seal are shown in Figure 4. Clearly, the direct rotor stiffness decreases with rotor speed whereas the cross stiffness increases. Also, the change in the cross stiffness is more sensitive to the change in speed as compared to the direct stiffness.

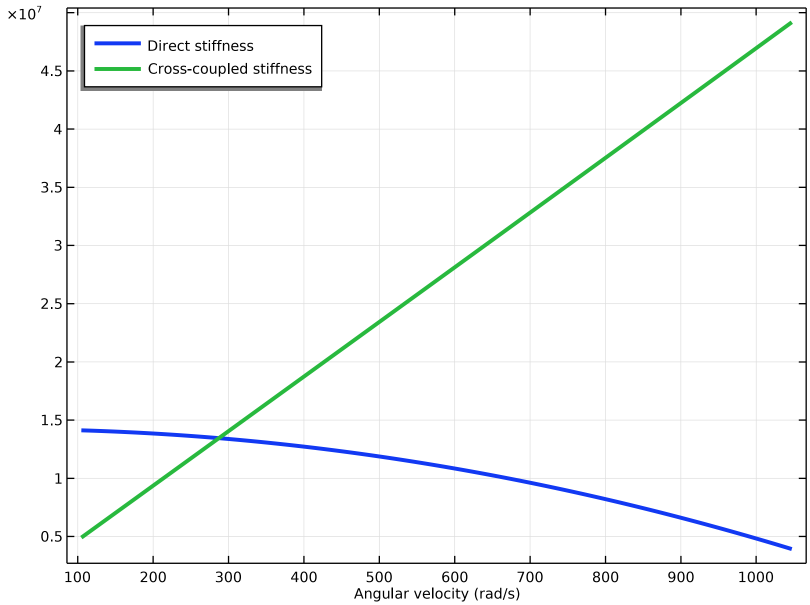

Figure 4: Stiffness of the balance piston seal.

The vertical displacement at impeller 5 is compared with and without seals in Figure 5. From this plot it is also possible to deduce that the vibration amplitudes of the rotor are significantly larger without seals. At higher rotor speeds, the amplitude of the displacement is growing without seals.

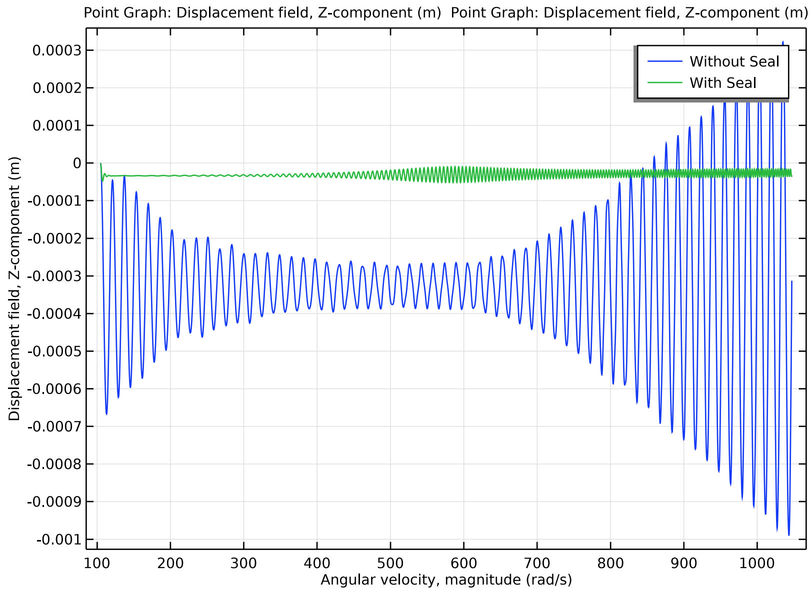

Figure 5: Comparison of the vertical displacement of the rotor at impeller 5.

Application Library path: `Rotordynamics_Module/Tutorials/rotor_stability_with_seal`

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** > **Rotordynamics** > **Beam Rotor (rotbm)**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters: Stations

Start by importing the parameters for the rotor, bearings, seals and impellers.

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 `rotor_stability_with_seal_stations.txt`.

5 In the **Label** text field, type `Parameters: Stations`.

Parameters: Rotor Diameters

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add** > **Parameters**.

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 `rotor_stability_with_seal_rotor_dia.txt`.

5 In the **Label** text field, type `Parameters: Rotor Diameters`.

Parameters: Bearings

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add** > **Parameters**.

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 `rotor_stability_with_seal_bearing.txt`.

5 In the **Label** text field, type `Parameters: Bearings`.

Parameters: Impellers

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add** > **Parameters**.

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 `rotor_stability_with_seal_impellers.txt`.

5 In the **Label** text field, type `Parameters: Impellers`.

Parameters: Seals

1 In the **Home** toolbar, click **Parameters** and choose **Add** > **Parameters**.

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 `rotor_stability_with_seal_seal_properties.txt`.

5 In the **Label** text field, type `Parameters: Seals`.

GEOMETRY 1

Polygon 1 (pol1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Polygon**.

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 From the **Data source** list, choose **Vectors**.

Use the station coordinates together with location of bearings, seals and impellers to create a 1D representation of the rotor.

4 In the **x** text field, type `x1 x2 x3 xb1 x4 x5 xs1 xd1 xs2 xd2 xs3 xd3 xs4 xd4 xs5 xd5 xs6 xd6 xs7 xd7 xs8 xd8 xs9 xd9 xs10 xd10 x6 xp x7 xb2 x8 x9 x10`.

5 In the **y** text field, type `0`.

6 In the **z** text field, type `0`.

7 Click **Build All Objects**.

DEFINITIONS

You can specify the diameter of the rotor between different stations by using as many **Rotor Cross Section** nodes as rotor segments. You can avoid many such nodes by using the interpolation function for the axial variation of the rotor diameter. You can use a small axial tolerance in the interpolation data to create the steps in the diameter near the stations.

Interpolation: Diameters

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

2 Right-click **Definitions** and choose **Functions** > **Interpolation**.

Import the text file containing the axial variation of the diameter.

3 In the **Settings** window for **Interpolation**, locate the **Definition** section.

4 Click **Load from File**.

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

6 In the **Label** text field, type `Interpolation: Diameters`.

7 Locate the **Definition** section. In the **Function name** text field, type `dia`.

8 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
dia	m

9 In the **Argument** table, enter the following settings:

Argument	Unit
t	m

10 Click **Plot**.

ADD MATERIAL

1 In the **Materials** 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 the **Add to Component** button in the window toolbar.

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

BEAM ROTOR (ROTBM)

The rotor speed is linearly increased from 1000 rpm to 10000 rpm in 2 seconds.

1 In the **Settings** window for **Beam Rotor**, locate the **Rotor Speed** section.

2 In the text field, type `4500[rpm/s]*t+1000[rpm]`.

Rotor Cross Section 1

Use the interpolation function with the axial coordinate as argument to specify the axial variation of the diameter.

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Beam Rotor (rotbm)** click **Rotor Cross Section 1**.

2 In the **Settings** window for **Rotor Cross Section**, locate the **Cross-Section Definition** section.

3 In the d_o text field, type `dia(x)`.

Gravity 1

In the **Physics** toolbar, click **Edges** and choose **Gravity**.

Journal Bearing 1

1 In the **Physics** toolbar, click **Points** and choose **Journal Bearing**.

2 Select Points 4 and 30 only.

3 In the **Settings** window for **Journal Bearing**, locate the **Bearing Properties** section.

4 From the **Bearing model** list, choose **Cylindrical hydrodynamic**.

5 From the μ list, choose **User defined**. In the associated text field, type `mu_b`.

6 In the C text field, type `Cb`.

7 In the R text field, type `Rb`.

8 In the L text field, type `Lb`.

9 Clear the **Include rotational stiffness** checkbox.

You use disk features to specify the impeller properties.

Disk 1

1 In the **Physics** toolbar, click **Points** and choose **Disk**.

2 Select Point 8 only.

3 In the **Settings** window for **Disk**, locate the **Disk Properties** section.

4 In the m text field, type `md1`.

5 In the I_p text field, type `2*Jd1`.

6 In the I_d text field, type `Jd1`.

7 From the **Center of mass** list, choose **Offset from selected points**.

8 In the z_r text field, type `e1`.

Disk 2-9

1 Right-click **Disk 1** and choose **Duplicate**.

2 In the **Settings** window for **Disk**, type `Disk 2-9` in the **Label** text field.

3 Locate the **Point Selection** section. Click **Clear Selection**.

4 Select Points 10, 12, 14, 16, 18, 20, 22, and 24 only.

5 Locate the **Disk Properties** section. In the m text field, type `md2`.

6 In the I_p text field, type `2*Jd2`.

7 In the I_d text field, type `Jd2`.

Disk 10

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Beam Rotor (rotbm)** right-click **Disk 1** and choose **Duplicate**.

2 In the **Settings** window for **Disk**, type `Disk 10` in the **Label** text field.

3 Locate the **Point Selection** section. Click **Clear Selection**.

4 Select Point 26 only.

5 Locate the **Disk Properties** section. In the m text field, type `md10`.

6 In the I_p text field, type `2*Jd10`.

7 In the I_d text field, type `Jd10`.

Disk 1, Disk 10, Disk 2-9

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Beam Rotor (rotbm)**, Ctrl-click to select **Disk 1**, **Disk 2-9**, and **Disk 10**.

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

Impellers

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

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(0,5e-4,2)`.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, expand the **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** node, then click **Fully Coupled 1**.

4 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.

Use the **Automatic Newton** solver to capture the nonlinearities in the bearings.

5 From the **Nonlinear method** list, choose **Automatic (Newton)**.

6 In the **Model Builder** window, click **Study 1**.

7 In the **Settings** window for **Study**, type `Study: without Seal` in the **Label** text field.

8 In the **Study** toolbar, click **Compute**.

RESULTS

Stress (Without Seal)

1 In the **Settings** window for **3D Plot Group**, type `Stress (Without Seal)` in the **Label** text field.

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

Follow the instructions to create the orbit plot at the bearing location.

Orbit

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

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

Point Graph 1

1 Right-click **Orbit** and choose **Point Graph**.

2 Select Point 4 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `w/Cb`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `v/Cb`.

7 Click to expand the **Coloring and Style** section. From the **Width** list, choose **3**.

8 Click to expand the **Legends** section. Select the **Show legends** checkbox.

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

10 In the table, enter the following settings:

Legends
`Without Seal`

Orbit

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

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

3 Select the **Preserve aspect ratio** checkbox.

4 In the **Orbit** toolbar, click **Plot**.

The study without seals is complete now. Next, add seals in the model and perform a new study to analyze their influence.

BEAM ROTOR (ROTBM)

Liquid Annular Seal 1

1 In the **Physics** toolbar, click **Points** and choose **Liquid Annular Seal**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Geometric Properties** section.

3 In the R text field, type `ds/2`.

4 In the L_s text field, type `Ls`.

5 In the C text field, type `Cs`.

6 Locate the **Fluid Properties** section. From the ρ list, choose **User defined**. In the associated text field, type `rho_f`.

7 From the μ list, choose **User defined**. In the associated text field, type `mu_f`.

8 Locate the **Flow Properties** section. In the ΔP text field, type `dPs`.

9 In the V_0 text field, type `60`.

The seals near the impellers are short in length. Use the Childs' model to account for the inlet swirling effect in these seals.

10 Locate the **Seal Model** section. From the list, choose **Childs**.

11 Locate the **Flow Properties** section. In the α text field, type `0.7`.

12 Select Point 7 only.

The seals at each stage are identical. Create 10 such features by duplicating and changing the selection.

Liquid Annular Seal 2

1 Right-click **Liquid Annular Seal 1** and choose **Duplicate**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 9 only.

Liquid Annular Seal 3

1 Right-click **Liquid Annular Seal 2** and choose **Duplicate**.

2 Select Point 11 only.

Liquid Annular Seal 4

1 Right-click **Liquid Annular Seal 3** and choose **Duplicate**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 13 only.

Liquid Annular Seal 1, Liquid Annular Seal 2, Liquid Annular Seal 3, Liquid Annular Seal 4

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Beam Rotor (rotbm)**, Ctrl-click to select **Liquid Annular Seal 1**, **Liquid Annular Seal 2**, **Liquid Annular Seal 3**, and **Liquid Annular Seal 4**.

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

Liquid Annular Seal 5

1 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

2 Click **Clear Selection**.

3 Select Point 15 only.

Liquid Annular Seal 6

1 In the **Model Builder** window, click **Liquid Annular Seal 6**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 17 only.

Liquid Annular Seal 7

1 In the **Model Builder** window, click **Liquid Annular Seal 7**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 19 only.

Liquid Annular Seal 8

1 In the **Model Builder** window, click **Liquid Annular Seal 8**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 21 only.

Liquid Annular Seal 9

1 Right-click **Component 1 (comp1)** > **Beam Rotor (rotbm)** > **Liquid Annular Seal 8** and choose **Duplicate**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 23 only.

Liquid Annular Seal 10

1 Right-click **Liquid Annular Seal 9** and choose **Duplicate**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Point Selection** section.

3 Click **Clear Selection**.

4 Select Point 25 only.

Liquid Annular Seal 1, Liquid Annular Seal 10, Liquid Annular Seal 2, Liquid Annular Seal 3, Liquid Annular Seal 4, Liquid Annular Seal 5, Liquid Annular Seal 6, Liquid Annular Seal 7, Liquid Annular Seal 8, Liquid Annular Seal 9

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Beam Rotor (rotbm)**, Ctrl-click to select **Liquid Annular Seal 1**, **Liquid Annular Seal 2**, **Liquid Annular Seal 3**, **Liquid Annular Seal 4**, **Liquid Annular Seal 5**, **Liquid Annular Seal 6**, **Liquid Annular Seal 7**, **Liquid Annular Seal 8**, **Liquid Annular Seal 9**, and **Liquid Annular Seal 10**.

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

Seals

1 In the **Settings** window for **Group**, type `Seals` in the **Label** text field.

2 In the **Model Builder** window, collapse the **Seals** node.

Next, add a balance piston seal.

Balance Piston Seal

1 In the **Physics** toolbar, click **Points** and choose **Liquid Annular Seal**.

2 In the **Settings** window for **Liquid Annular Seal**, locate the **Geometric Properties** section.

3 In the R text field, type `dp/2`.

4 In the L_s text field, type `Lp`.

5 In the C text field, type `Cp`.

6 Locate the **Fluid Properties** section. From the ρ list, choose **User defined**. In the associated text field, type `rho_f`.

7 From the μ list, choose **User defined**. In the associated text field, type `mu_f`.

8 Locate the **Flow Properties** section. In the ΔP text field, type `dPp`.

9 In the V_0 text field, type `90`.

10 Select Point 28 only.

11 In the **Label** text field, type `Balance Piston Seal`.

The balance piston seal has a finite length. The **Black and Jenssen** model is preferred in this case.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.
2 Go to the **Add Study** window.
3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Time Dependent**.
4 Click the **Add Study** button in the window toolbar.
5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
2 In the **Output times** text field, type `range(0,5e-4,2)`.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node.
3 In the **Model Builder** window, expand the **Study 2** > **Solver Configurations** > **Solution 2 (sol2)** > **Time-Dependent Solver 1** node, then click **Fully Coupled 1**.
4 In the **Settings** window for **Fully Coupled**, locate the **Method and Termination** section.
5 From the **Nonlinear method** list, choose **Automatic (Newton)**.
6 In the **Model Builder** window, click **Study 2**.
7 In the **Settings** window for **Study**, type `Study: with Seal` in the **Label** text field.
8 In the **Study** toolbar, click **Compute**.

RESULTS

Stress (With Seal)

The stress in the rotor is a default plot, see Figure 2.

1 In the **Settings** window for **3D Plot Group**, type `Stress (With Seal)` in the **Label** text field.
2 Locate the **Title** section. From the **Title type** list, choose **Label**.
3 Click the **Zoom Extents** button in the **Graphics** toolbar.

Point Graph 1

Duplicate the **Point Graph 1** in the **Orbit** plot and change the solution to compare the response with and without seals. This plot is shown in Figure 3.

Point Graph 2

1 In the **Model Builder** window, under **Results** > **Orbit** right-click **Point Graph 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **Study: with Seal/Solution 2 (sol2)**.

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

Legends
`With Seal`

5 In the **Orbit** toolbar, click **Plot**.

The seal stiffness plays an important role in determining the response of the rotor. Use the following instructions to plot the variation of the balance piston seal stiffness with rotor speed as shown in Figure 4.

Balance Piston Seal Stiffness

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

2 In the **Settings** window for **1D Plot Group**, type `Balance Piston Seal Stiffness` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: with Seal/Solution 2 (sol2)**.

Global 1

1 Right-click **Balance Piston Seal Stiffness** 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)** > **Beam Rotor** > **Balance Piston Seal** > **rotbm.las11.Kd - Direct stiffness - N/m**.

3 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Beam Rotor** > **Balance Piston Seal** > **rotbm.las11.kc - Cross-coupled stiffness - N/m**.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `rotbm.las11.Omega`.

6 Click to expand the **Coloring and Style** section. From the **Width** list, choose **3**.

7 In the **Balance Piston Seal Stiffness** toolbar, click **Plot**.

Balance Piston Seal Stiffness

1 In the **Model Builder** window, click **Balance Piston Seal Stiffness**.

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

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

Use the following instructions to compare the vertical displacement of the rotor at impeller 5 as shown in Figure 5.

Vertical Displacement at Impeller 5

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

2 In the **Settings** window for **1D Plot Group**, type `Vertical Displacement at Impeller 5` in the **Label** text field.

Point Graph: Without Seal

1 Right-click **Vertical Displacement at Impeller 5** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, type `Point Graph: Without Seal` in the **Label** text field.

3 Select Point 16 only.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `w`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `rotbm.Ov`.

7 Locate the **Legends** section. Select the **Show legends** checkbox.

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

9 In the table, enter the following settings:

Legends
Without Seal

Point Graph: With Seal

1 Right-click **Point Graph: Without Seal** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, type `Point Graph: With Seal` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study: with Seal/Solution 2 (sol2)**.

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

Legends
With Seal

5 In the **Vertical Displacement at Impeller 5** toolbar, click **Plot**.

Now, you can disable seals from the first study to allow the recomputation without seals.

Study: without Seal

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study: without Seal** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** checkbox.

4 In the tree, select **Component 1 (comp1)** > **Beam Rotor (rotbm)** > **Seals** and **Component 1 (comp1)** > **Beam Rotor (rotbm)** > **Balance Piston Seal**.

5 Click **Disable**.