

# Stability of a Turbocharger Under the Influence of Cross-Coupled Bearing Forces

## *Introduction*

---

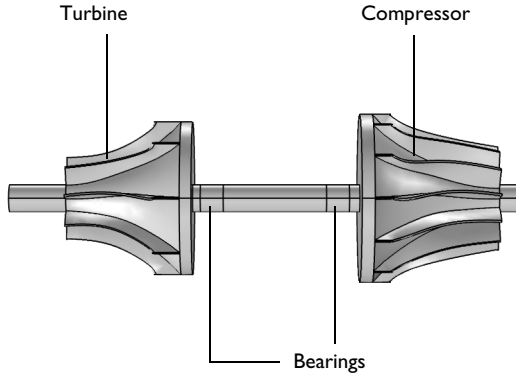
A turbocharger is often supported by hydrodynamic journal bearings. Such bearings naturally have the cross-coupled forces present in them. These cross-coupled forces act as a negative damping in the system. Due to this, near the critical speed, the vibration amplitude in the turbocharger can become large, ultimately leading to the bearing failure. In this example we study the influence of these cross-coupled forces on the dynamics of the rotor.

Variation in the eigenfrequencies and logarithmic decrement with the rotational speed of the rotor gives the idea of the stability state of the overall system. Response of the turbocharger due to mass eccentricity at the turbine and compressor is also studied. The waterfall diagram clearly shows that the response amplitude is maximum in the resonance conditions.

## *Model Definition*

---

The model consists of a turbocharger rotor supported by two bearings, one near the compressor and another near turbine, making both the compressor and turbine overhung on the shaft. The geometry of the rotor is shown in [Figure 1](#).



*Figure 1: Rotor geometry.*

Two different analyses are performed:

- An eigenfrequency analysis.
- A frequency response analysis for different angular speeds of the rotor. This analysis looks at the frequency spectrum of the rotor and how it changes with the rpm.

### CASE 1 — EIGENFREQUENCY ANALYSIS

In this case, eigenfrequency analysis is performed for the different angular speed of the turbocharger. Structural damping is added to damp the high frequency vibrations of the rotor. The bearings are modeled by equivalent stiffness and damping constants. Bending stiffness and damping in the bearings are neglected.

Properties of the bearings used in this analysis are given in [Table 1](#):

TABLE 1: BEARING PROPERTIES.

PROPERTY	VALUE
$k_{yy}$ (N/m)	$1 \cdot 10^8$
$k_{zz}$ (N/m)	$1 \cdot 10^8$
$k_{yz}$ (N/m)	$4 \cdot 10^7$
$k_{zy}$ (N/m)	$-4 \cdot 10^7$

Two cases of the bearing stiffness are considered. In first, the cross-coupled stiffness  $k_{yz}$  and  $k_{zy}$  are ignored and in second all the four components of the stiffness are present. The angular speed of the rotor is varied from 10,000 rpm to 150,000 rpm in steps of 10,000 rpm. The variations in natural frequencies and logarithmic decrements with angular speed of the rotor are analyzed.

### CASE2 — FREQUENCY RESPONSE ANALYSIS

In this case, you analyze the harmonic response of the turbocharger rotor due to the mass eccentricities at both turbine and compressor. The angular speed of the shaft is varied from 10,000 rpm to 150,000 rpm in steps of 10,000 rpm. Frequency is varied from 50 to 5000 Hz in steps of 50 Hz. Variations in the frequency spectrum of the displacement at a point on the rotor is studied.

### EIGENFREQUENCY ANALYSIS

The mode shape of the turbocharger for the fourth mode is shown in [Figure 2](#). In this mode primarily the compressor undergoes the whirl of significant amplitude as compared to the other parts of the rotor. Tilt in the compressor is also significant.

p=1,  $\Omega\omega=1.5E5$  Eigenfrequency=1777.3-274.01i Hz Surface: Displacement magnitude (m)

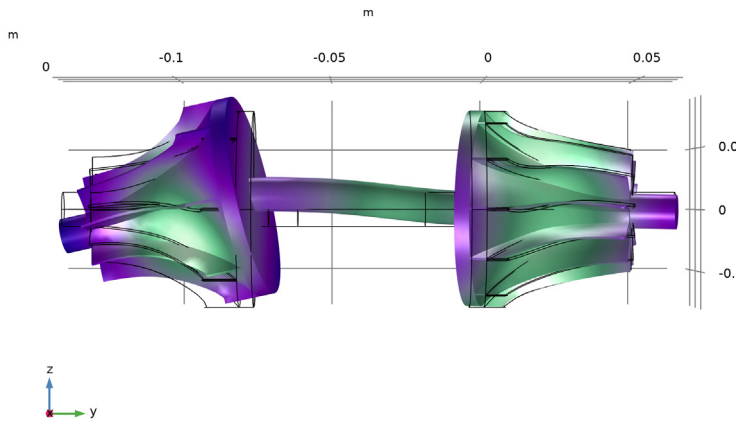
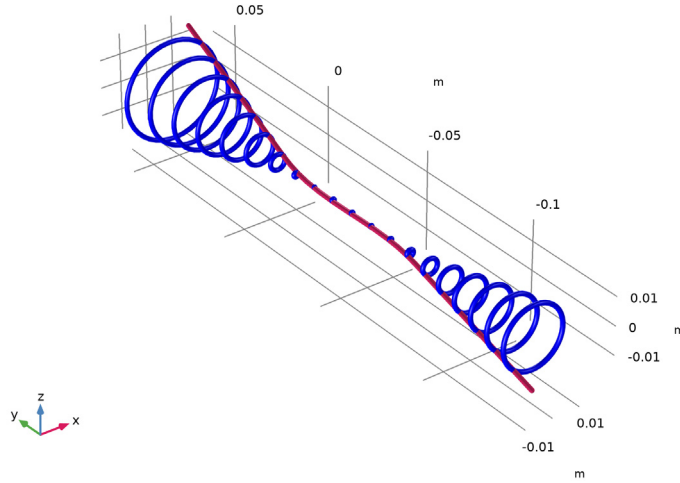


Figure 2: Mode shape of the turbocharger.

The whirl plot for the sixth mode is shown in [Figure 3](#). In this mode whirling of both compressor and turbine is significant.

p=1,  $\Omega\omega=1.5E5$  Eigenfrequency=2700.3+18.835i Hz Whirl: Displacement field



*Figure 3: Whirl plot.*

Campbell plots, shown in [Figure 4](#) and [Figure 5](#), compares the eigenfrequency variation of the rotor excluding and including the cross-coupled stiffness of the bearings, respectively. There is no appreciable change in the eigenfrequency variation due to cross-coupled stiffness except that third and fourth modes frequencies are more closer in the presence of cross-coupled stiffness.

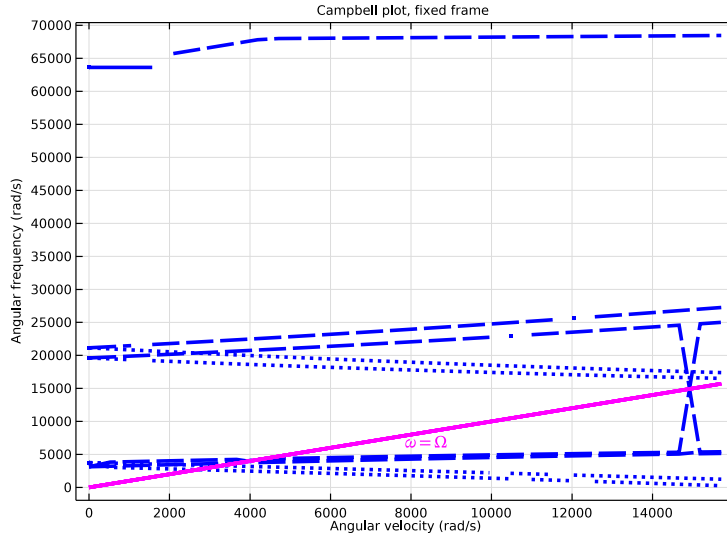


Figure 4: Campbell plot without cross-coupled stiffness.

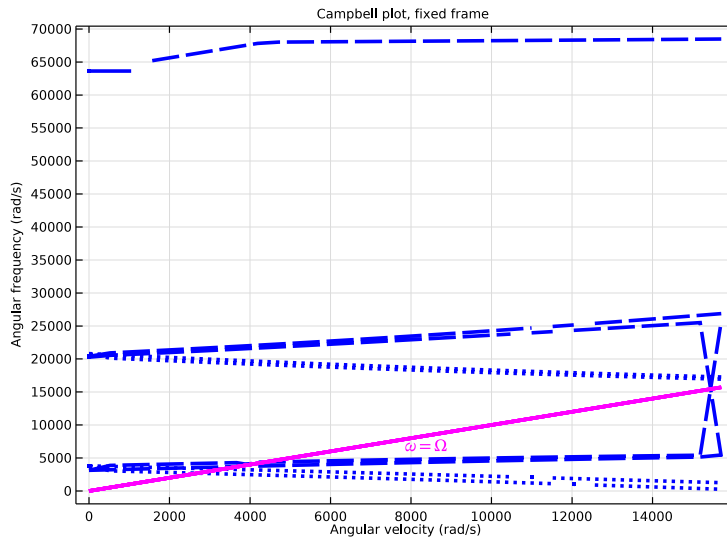


Figure 5: Campbell plot with cross-coupled stiffness.

The logarithmic decrement is a parameter that gives the stability state of the system. If the logarithmic decrement is positive the response is said to be stable and vice versa. A zero value indicates no damping in that particular mode. The expression for the logarithmic decrement in terms of eigenvalues is:

$$\delta = 2\pi \frac{\text{imag}(\omega)}{\text{real}(\omega)}$$

A plot of the logarithmic decrement as a function of the rotor angular speed is shown in [Figure 6](#) and [Figure 7](#). This plot shows how the damping in a particular mode changes with the angular speed of the rotor. The logarithmic decrement in the absence of cross-coupled stiffness is positive indicating that the natural modes are stable in the absence of cross-coupled bearing stiffness. In the presence of cross-coupled stiffness, many modes have negative logarithmic decrement even at small rotor speeds. This indicates that the presence of cross-coupled stiffness makes the vibrational modes unstable and hence it is dangerous to operate the turbocharger rotor at these speeds.

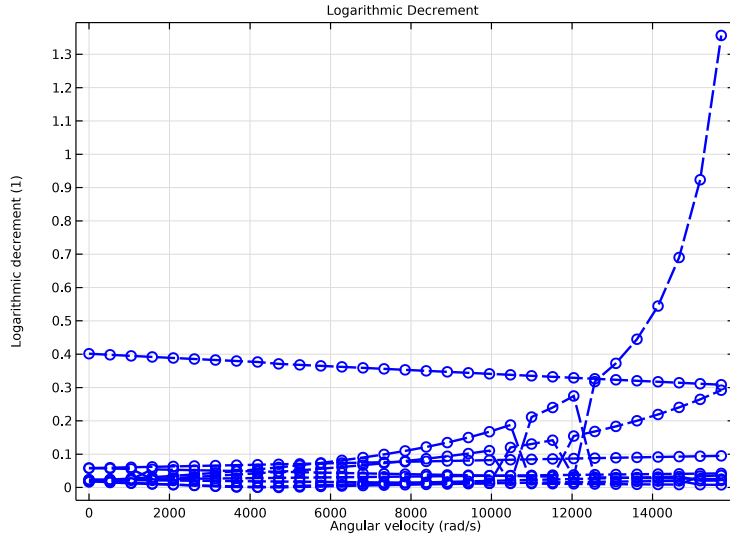


Figure 6: Logarithmic decrement without cross-coupled stiffness.

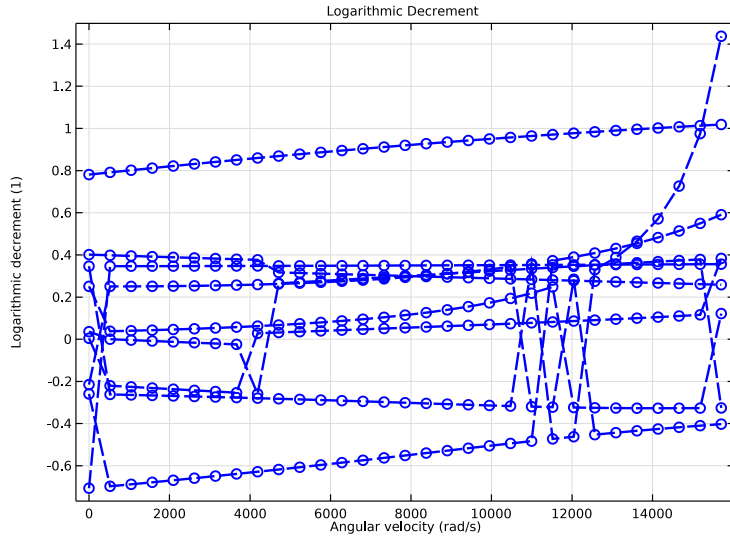


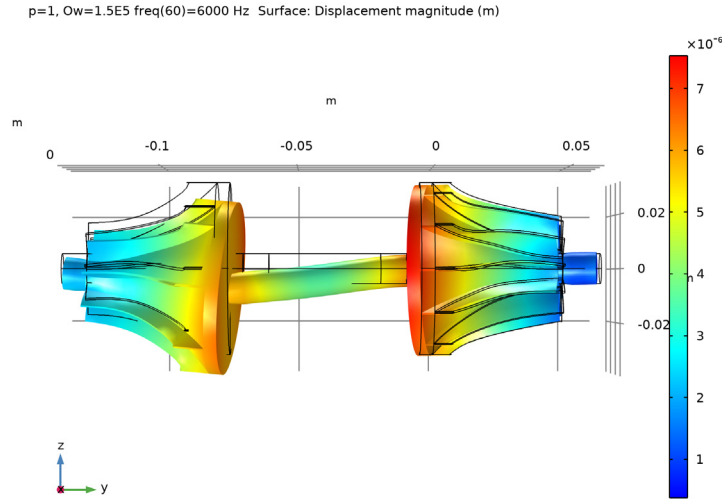
Figure 7: Logarithmic decrement with cross-coupled stiffness.



Cross-coupled stiffness in the hydrodynamic bearings can be reduced by changing the bearing design. For example, the tilted pad bearings are known to have the least cross-coupled stiffness. Other way to control the response is to add more damping in the system, for example, using the squeeze film dampers at various locations.

## FREQUENCY RESPONSE ANALYSIS

The displacement response with cross-coupled stiffness of the turbocharger operating at 150,000 rpm and subjected to a harmonic loading at 3000 Hz is shown in [Figure 8](#).



*Figure 8: Displacement response at 3000 Hz.*

The waterfall plot for the displacement at the first bearing location is shown in [Figure 9](#) and [Figure 10](#). The waterfall plot shows the variation in the frequency spectrum of the rotor with the change in its angular speed. In the absence of the cross-coupling forces in the bearing ([Figure 9](#)) many modes are excited due to the mass eccentricity in the turbine and compressors. If the cross-coupling forces are present ([Figure 10](#)) not all the modes are excited. To excite the other modes in the presence of cross-coupling forces a different kind of excitation might be needed.

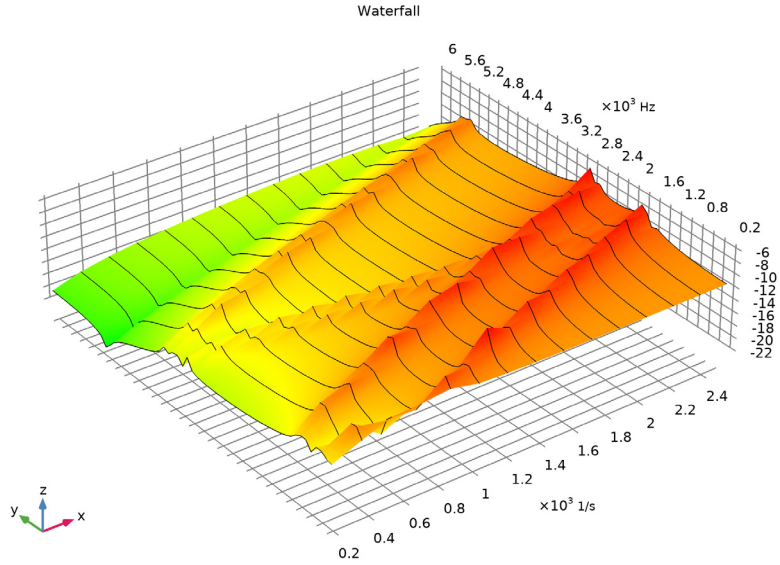


Figure 9: Waterfall plot without cross-coupled stiffness.

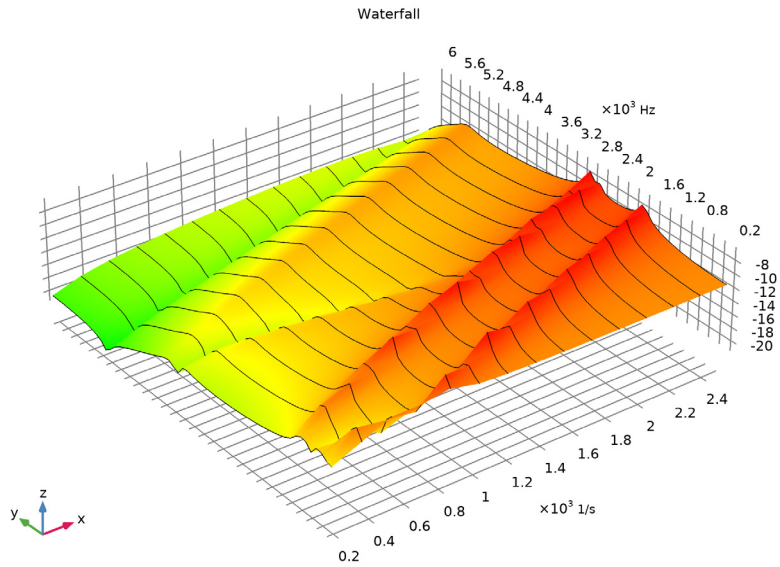


Figure 10: Waterfall plot with cross-coupled stiffness.

---

**Application Library path:** Rotordynamics\_Module/Automotive\_and\_Aerospace/  
turbocharger\_stability\_analysis


---

### *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>Solid Rotor (rotsld)**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **General Studies>Eigenfrequency**.
- 6 Click  **Done**.

#### **GEOMETRY I**

##### *Import I (impl)*

Import the turbocharger geometry.

- 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  
turbocharger\_stability\_analysis.mphbin.
- 5 Click  **Build All Objects**.

#### **GLOBAL DEFINITIONS**

Create the model parameters.



##### *Parameters I*

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

- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 In the table, enter the following settings:

Name	Expression	Value	Description
p	0	0	Parameter to include/exclude cross-coupled stiffness
Ow	10000[rpm]	166.67 l/s	Angular speed of the rotor
e	1e-5[m]	1E-5 m	Mass eccentricity of turbine/compressor

#### 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 the right end of the **Add to Component** split button in the window toolbar.
- 5 From the menu, choose **Component 1 (comp1)**.
- 6 In the **Home** toolbar, click  **Add Material** to close the **Add Material** window.


#### DEFINITIONS

Create the selection for the compressor and turbine for later use.

##### *Compressor*

- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 Select Domain 2 only.
- 3 In the **Settings** window for **Explicit**, type Compressor in the **Label** text field.

##### *Turbine*

- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 Select Domain 1 only.
- 3 In the **Settings** window for **Explicit**, type Turbine in the **Label** text field.

#### SOLID ROTOR (ROTSLD)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Solid Rotor (rotsld)**.
  - 2 In the **Settings** window for **Solid Rotor**, locate the **Rotor Speed** section.
  - 3 In the text field, type Ow.
- Set the **Discretization** to **Linear** to save the computation time. A **Quadratic** interpolation can be used for better accuracy.


- 4 Click to expand the **Discretization** section. From the **Displacement field** list, choose **Linear**.

*Linear Elastic Material 1*

Add the material damping in the shaft.

- 1 In the **Model Builder** window, under **Component 1 (comp1)>Solid Rotor (rotsld)** click **Linear Elastic Material 1**.

*Damping 1*

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Damping**.
- 2 In the **Settings** window for **Damping**, locate the **Damping Settings** section.
- 3 In the  $\alpha_{dM}$  text field, type 6.04.
- 4 In the  $\beta_{dK}$  text field, type 2e-6.

*First Support 1*

- 1 In the **Model Builder** window, click **First Support 1**.
- 2 Select Points 209 and 210 only.

*Second Support 1*

- 1 In the **Model Builder** window, click **Second Support 1**.
- 2 Select Points 251 and 252 only.


*Fixed Axial Rotation 1*

- 1 In the **Model Builder** window, click **Fixed Axial Rotation 1**.
- 2 Select Boundaries 6, 7, 134, and 136 only.

*Fixed Axial Rotation 2*

- 1 Right-click **Component 1 (comp1)>Solid Rotor (rotsld)>Fixed Axial Rotation 1** and choose **Duplicate**.
- 2 Select Boundaries 10, 11, 146, and 149 only.

*Journal Bearing 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Journal Bearing**.
- 2 Select Boundaries 85, 86, 138, and 139 only.
- 3 In the **Settings** window for **Journal Bearing**, locate the **Bearing Orientation** section.
- 4 Specify the **Orientation vector defining local y direction** vector as

1	x
---	---

0	y
0	z

**5** Locate the **Bearing Properties** section. From the **Bearing model** list, choose **Total spring and damping constant**.

**6** In the  $\mathbf{k}_u$  table, enter the following settings:

1e8	4e7*p
-4e7*p	1e8

**7** In the  $\mathbf{k}_\theta$  table, enter the following settings:

0	0
0	0

The parameter p is used for enabling and disabling the cross-coupled stiffness.

#### *Journal Bearing 2*

**1** Right-click **Journal Bearing 1** and choose **Duplicate**.

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

**3** Click  **Clear Selection**.

**4** Select Boundaries 91, 92, 142, and 143 only.

**5** Locate the **Bearing Properties** section. In the  $\mathbf{k}_u$  table, enter the following settings:

1e8	1e7*p
-1e7*p	1e8

**6** In the  $\mathbf{k}_\theta$  table, enter the following settings:

0	0
0	0

#### *Rigid Domain: Turbine*

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

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

**3** From the **Selection** list, choose **Turbine**.


**4** In the **Label** text field, type Rigid Domain: Turbine.

**5** Locate the **Center of Rotation** section. Select the **Offset** check box.

6 Specify the  $\mathbf{X}_{\text{offset}}$  vector as

0	x
0	y
e	z


*Rigid Domain: Compressor*

- 1 In the **Physics** toolbar, click  **Domains** and choose **Rigid Domain**.
- 2 In the **Settings** window for **Rigid Domain**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **Compressor**.
- 4 In the **Label** text field, type Rigid Domain: Compressor.
- 5 Locate the **Center of Rotation** section. Select the **Offset** check box.
- 6 Specify the  $\mathbf{X}_{\text{offset}}$  vector as

e	x
0	y
0	z

## MESH I


*Swept I*

- 1 In the **Mesh** toolbar, click  **Swept**.
- 2 In the **Settings** window for **Swept**, locate the **Domain Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Select Domains 3–7 only.

*Free Tetrahedral I*



In the **Mesh** toolbar, click  **Free Tetrahedral**.

*Size I*

- 1 In the **Model Builder** window, right-click **Swept I** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 From the **Predefined** list, choose **Extra fine**.
- 4 Click  **Build All**.

## STUDY I


### Parametric Sweep

- 1 In the **Study** toolbar, click  **Parametric Sweep**.
- 2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.
- 3 Click  **Add** twice.
- 4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
p (Parameter to include/exclude cross-coupled stiffness)	0 1	
Ow (Angular speed of the rotor)	range (0, 5000, 150000)	rpm

- 5 From the **Sweep type** list, choose **All combinations**.




### Step 1: Eigenfrequency

- 1 In the **Model Builder** window, click **Step 1: Eigenfrequency**.
- 2 In the **Settings** window for **Eigenfrequency**, locate the **Study Settings** section.
- 3 Select the **Desired number of eigenfrequencies** check box.
- 4 In the associated text field, type 9.
- 5 In the **Study** toolbar, click  **Compute**.

## RESULTS

### Mode Shape (rotsld)

The following instructions will generate the mode shape shown in [Figure 2](#).

- 1 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
- 2 From the **Eigenfrequency (Hz)** list, choose **1777.3-274.01i**.
- 3 Click the  **Go to YZ View** button in the **Graphics** toolbar.
- 4 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 5 In the **Mode Shape (rotsld)** toolbar, click  **Plot**.




You can select the different eigenfrequencies from the list to analyze the corresponding mode shapes.

### Whirl (rotsld)

The following instructions will generate the whirl plot shown in [Figure 3](#).






### *Whirl I*

- 1 In the **Model Builder** window, expand the **Whirl (rotsld)** node, then click **Whirl I**.
- 2 In the **Settings** window for **Whirl**, locate the **Data** section.
- 3 From the **Eigenfrequency (Hz)** list, choose **2700.3+18.835i**.
- 4 Locate the **Coloring and Style** section. In the **Number of planes** text field, type 1.
- 5 In the **Number of rings** text field, type 20.
- 6 From the **Color table** list, choose **HeatCamera**.
- 7 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 8 In the **Whirl (rotsld)** toolbar, click  **Plot**.
- 9 Click  **Plot**.


### *Campbell Plot, Fixed Frame (rotsld)*

The Campbell plots excluding and including the cross coupled stiffness effects are shown in [Figure 4](#) and [Figure 5](#), respectively. Follow the instructions below to reproduce them.

- 1 In the **Model Builder** window, click **Campbell Plot, Fixed Frame (rotsld)**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Data** section.
- 3 From the **Parameter selection (p)** list, choose **First**.
- 4 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 5 In the **Campbell Plot, Fixed Frame (rotsld)** toolbar, click  **Plot**.  
Switch the parameter p from **first** to **last** to analyze the effect of the cross-coupled stiffness.
- 6 From the **Parameter selection (p)** list, choose **Last**.
- 7 In the **Campbell Plot, Fixed Frame (rotsld)** toolbar, click  **Plot**.



### *Logarithmic Decrement*

The following instructions generate the **Logarithmic decrement** plots shown in [Figure 6](#) and [Figure 7](#).

- 1 In the **Home** toolbar, click  **Add Plot Group** and choose **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Logarithmic Decrement** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.
- 4 From the **Parameter selection (p)** list, choose **First**.
- 5 Click to expand the **Title** section. From the **Title type** list, choose **Label**.



- 6 Right-click **Logarithmic Decrement** and choose **Show Legends**.

#### *Global 1*

- 1 Right-click **Logarithmic Decrement** 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)>Solid Rotor>Whirl frequencies>rotsld.log\_dec - Logarithmic decrement**.
- 3 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Outer solutions**.
- 4 From the **Parameter** list, choose **Expression**.
- 5 In the **Expression** text field, type `rotsld.0vg`.
- 6 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.
- 7 From the **Color** list, choose **Blue**.
- 8 In the **Width** text field, type 2.
- 9 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.
- 10 From the **Positioning** list, choose **In data points**.
- 11 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 12 In the **Logarithmic Decrement** toolbar, click  **Plot**.


Switch the value of the parameter *p* from **First** to **Last** to analyze the effect of cross-coupled stiffness on logarithmic decrement.

#### *Logarithmic Decrement*

- 1 In the **Model Builder** window, click **Logarithmic Decrement**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Data** section.
- 3 From the **Parameter selection (p)** list, choose **Last**.
- 4 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 5 In the **Logarithmic Decrement** toolbar, click  **Plot**.

#### *Animation 1*

Finally you can create the animation of the **Whirl** using the following instructions.



- 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 **Whirl (rotsld)**.
- 4 Locate the **Animation Editing** section. From the **Sequence type** list, choose **Dynamic data extension**.

5 Right-click **Animation 1** and choose **Play**.

**ROOT**

**Eigenfrequency Analysis** is finished now. Now you will analyze the harmonic response of the turbocharger due to eccentric forces on turbine and compressor.

**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>Frequency Domain**.
- 4 Click **Add Study** in the window toolbar.
- 5 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

**STUDY 2**


*Step 1: Frequency Domain*

- 1 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.
- 2 In the **Frequencies** text field, type range (100,100,6000).
- 3 In the **Home** toolbar, click **Desktop Layout** and choose **Reset Desktop**.

*Parametric Sweep*

- 1 In the **Study** toolbar, click  **Parametric Sweep**.
- 2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.
- 3 Click  **Add** twice.
- 4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
p (Parameter to include/exclude cross-coupled stiffness)	0 1	
Ow (Angular speed of the rotor)	range (1e4, 1e4, 15e4)	rpm

- 5 From the **Sweep type** list, choose **All combinations**.
- 6 In the **Study** toolbar, click  **Compute**.


## RESULTS

### *Displacement (rotsld)*



The first default plot for **Study 2** is a stress plot, which is only meaningful in an elastic domain. Change this plot to show the displacement response as in [Figure 8](#) using the following instructions.

- 1 In the **Settings** window for **3D Plot Group**, type Displacement (rotsld) in the **Label** text field.

### *Surface*


- 1 In the **Model Builder** window, expand the **Displacement (rotsld)** node, then click **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type rotsld.disp.
- 4 In the **Displacement (rotsld)** toolbar, click  **Plot**.

### *Displacement (rotsld)*


- 1 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 2 In the **Model Builder** window, click **Displacement (rotsld)**.
- 3 In the **Displacement (rotsld)** toolbar, click  **Plot**.

### *Cut Point 3D I*





The following instructions generate the Waterfall plots shown in [Figure 9](#) and [Figure 10](#). To do that we start by creating a **Cut Point** at the center of the compressor end of the shaft.

- 1 In the **Results** toolbar, click  **Cut Point 3D**.
- 2 In the **Settings** window for **Cut Point 3D**, locate the **Point Data** section.
- 3 In the **X** text field, type 0.
- 4 In the **Y** text field, type 0.0624.
- 5 In the **Z** text field, type 0.
- 6 Locate the **Data** section. From the **Dataset** list, choose **Study 2/ Parametric Solutions 2 (sol66)**.

### *Waterfall plot*

- 1 In the **Results** toolbar, click  **3D Plot Group**.
- 2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Point 3D I**.
- 4 In the **Label** text field, type Waterfall plot.


### Waterfall 1

- 1 In the **Waterfall plot** toolbar, click  **More Plots** and choose **Waterfall**.
- 2 In the **Settings** window for **Waterfall**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Point 3D 1**.
- 4 From the **Parameter selection (p)** list, choose **First**.
- 5 Locate the **Expression** section. In the **Expression** text field, type  $\log(\text{abs}(u))$ .
- 6 Locate the **x-Axis Data** section. In the **Expression** text field, type  $0w$ .
- 7 Locate the **y-Axis Data** section. In the **Expression** text field, type  $\text{freq}$ .
- 8 Locate the **Coloring and Style** section. From the **Color table** list, choose **TrafficLight**.
- 9 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 10 In the **Waterfall plot** toolbar, click  **Plot**.
- 11 Click the  **Scene Light** button in the **Graphics** toolbar.



Adjust the grids in the **View** corresponding to the **Waterfall Plot**.

- 12 In the **Model Builder** window, expand the **Results>Views** node.

### Camera

- 1 In the **Model Builder** window, expand the **Results>Views>View 3D 3** node, then click **Camera**.
- 2 In the **Settings** window for **Camera**, locate the **Grid** section.
- 3 Select the **Manual spacing** check box.
- 4 In the **x spacing** text field, type 200.
- 5 In the **y spacing** text field, type 200.
- 6 In the **z spacing** text field, type 2.
- 7 Click  **Update**.

### Waterfall 1

- 1 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 2 In the **Model Builder** window, click **Waterfall 1**.
- 3 In the **Settings** window for **Waterfall**, locate the **Data** section.
- 4 From the **Parameter selection (p)** list, choose **Last**.
- 5 In the **Waterfall plot** toolbar, click  **Plot**.

### Animation 1

Finally use the following instructions to create the animation of the **Displacement** response.

### *Animation 2*

- 1** In the **Model Builder** window, under **Results>Export** right-click **Animation 1** and choose **Duplicate**.
- 2** In the **Settings** window for **Animation**, locate the **Scene** section.
- 3** From the **Subject** list, choose **Displacement (rotsld)**.
- 4** Right-click **Animation 2** and choose **Play**.