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 external forces 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.

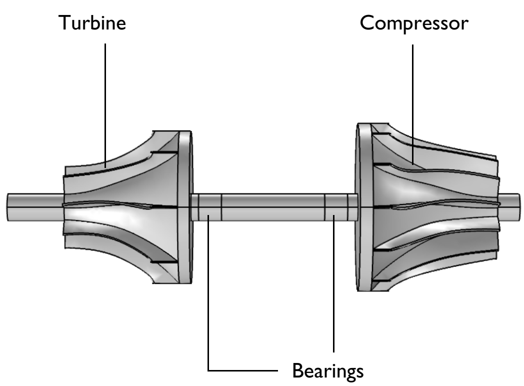

Figure 1: Rotor geometry.

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 speeds 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)	$1\cdot10^8$
k_{zz} (N/m)	$1\cdot10^8$
k_{yz} (N/m)	$4\cdot10^7$
k_{zy} (N/m)	$-4\cdot10^7$

Two cases of the bearing stiffness are considered. In the first, the cross-coupled stiffness k_{yz} and k_{zy} are ignored and in the second all four components of the stiffness are present. The angular speed of the rotor is varied from 0 rpm to 100,000 rpm in steps of 5,000 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 2,000 rpm to 100,000 rpm in steps of 2,000 rpm. The frequency is varied from 100 to 3000 Hz in steps of 100 Hz. Variations in the frequency spectrum of the displacement at a point on the rotor is studied.

Results and Discussion

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 both the turbine and the compressor is also significant.

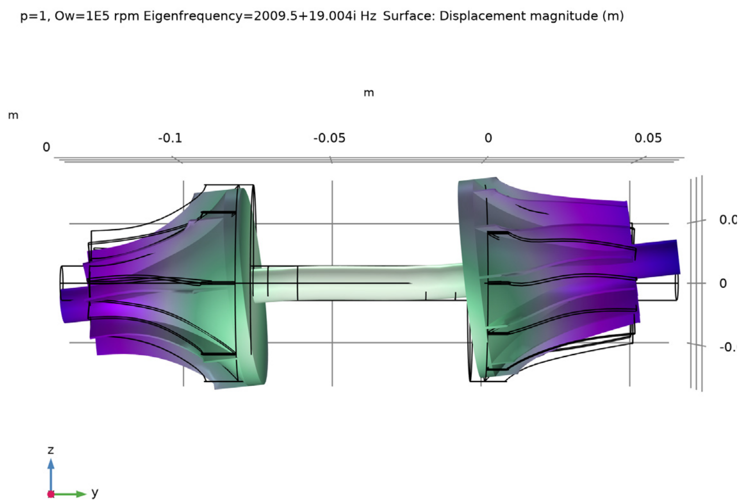

Figure 2: Mode shape of the turbocharger.

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

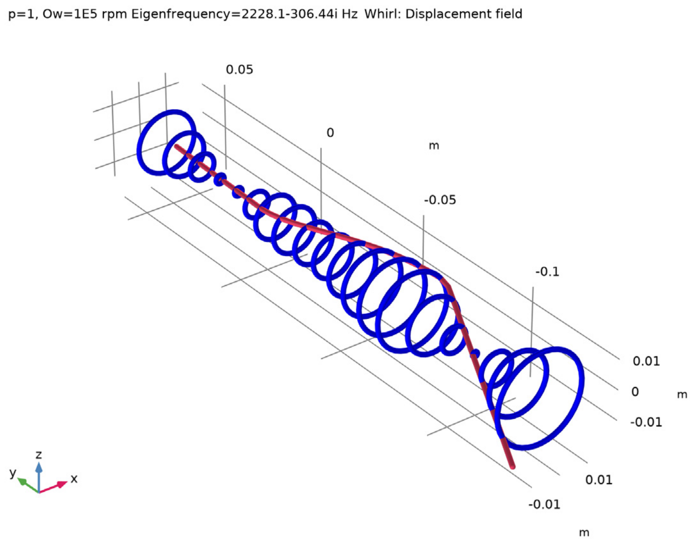

Figure 3: Whirl plot.

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.

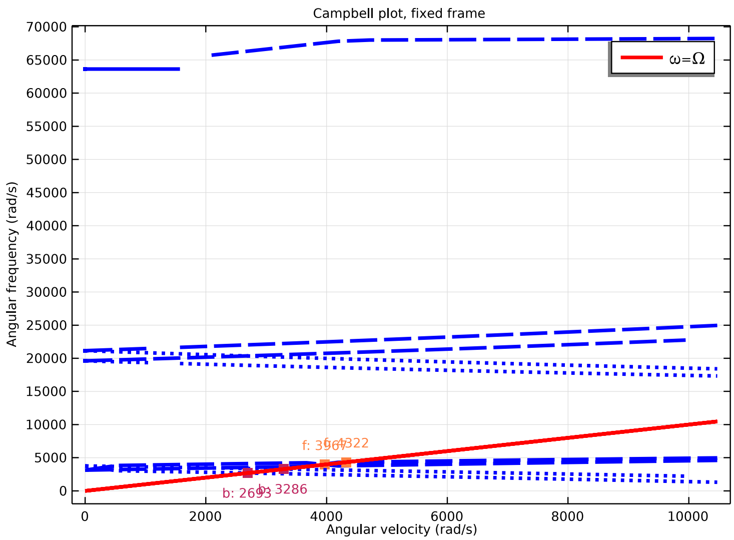

Figure 4: Campbell plot without cross-coupled stiffness.

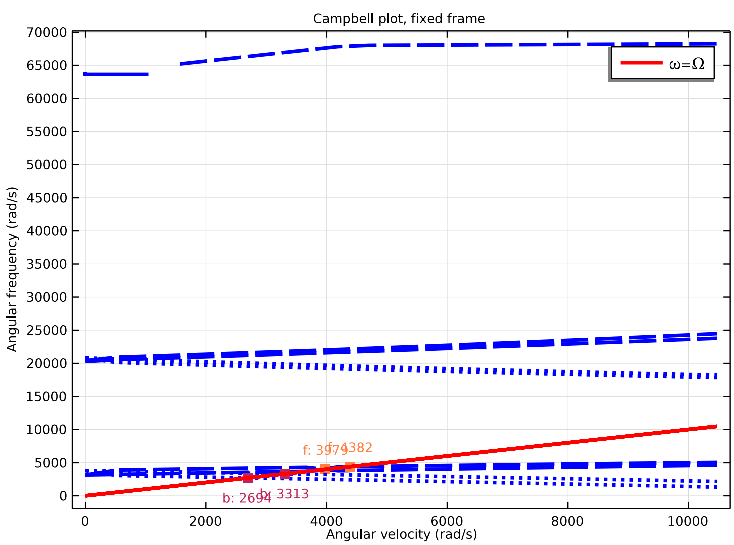

Figure 5: Campbell plot with cross-coupled stiffness.

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:

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

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.

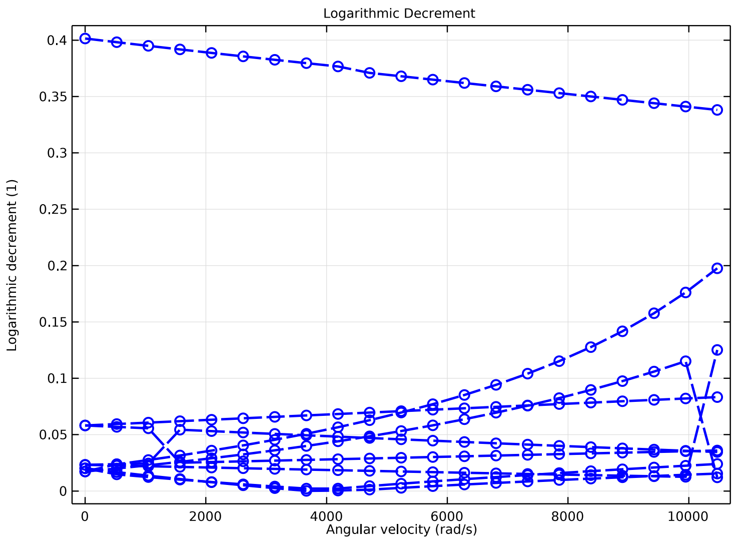

Figure 6: Logarithmic decrement without cross-coupled stiffness.

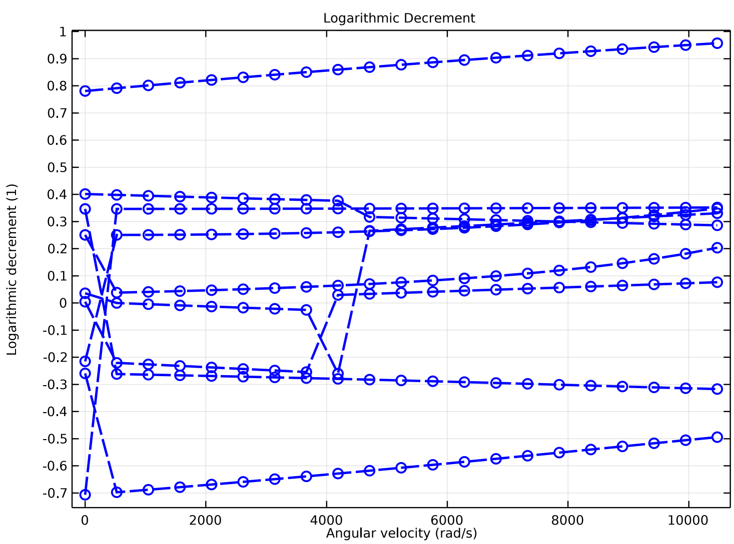

Figure 7: Logarithmic decrement with cross-coupled stiffness.

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 100,000 rpm and subjected to a harmonic loading at 3000 Hz is shown in Figure 8.

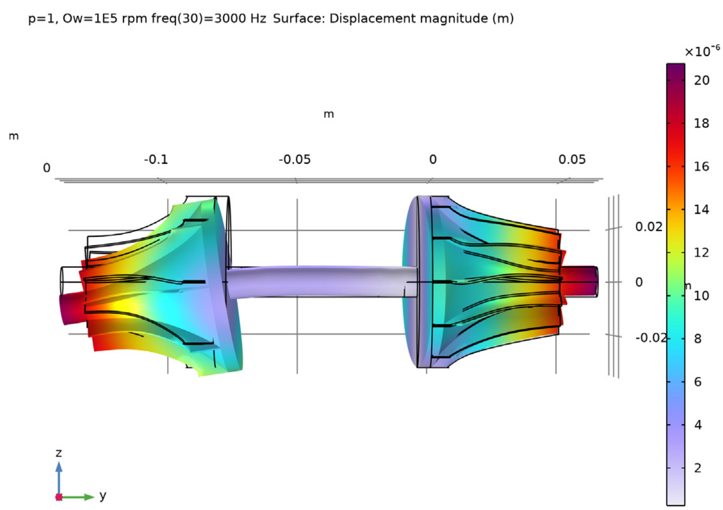

Figure 8: Displacement response at 3000 Hz.

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) large peaks are observed for certain combinations of the loading frequency and rotor speed. If the cross-coupling forces are present (Figure 10) peaks are more or less uniform.

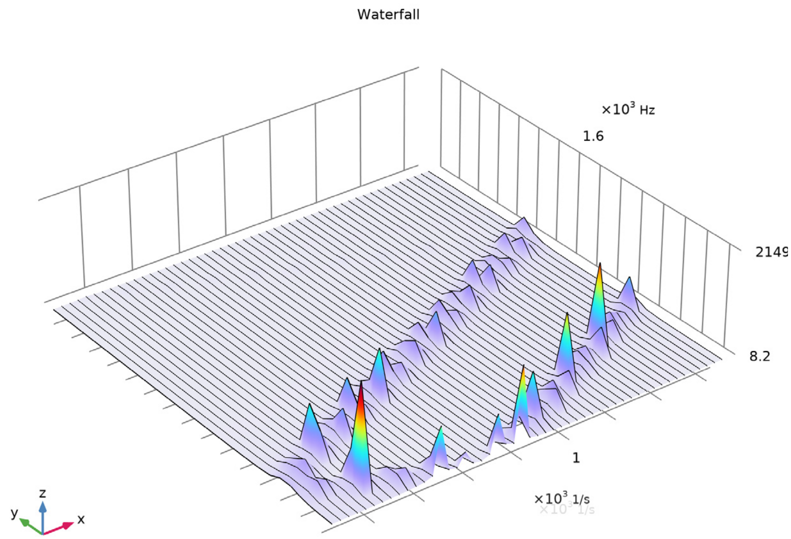

Figure 9: Waterfall plot without cross-coupled stiffness.

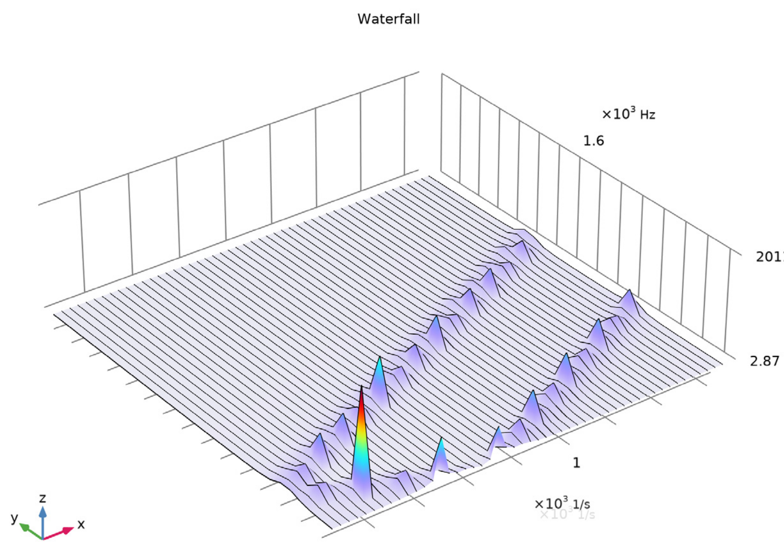

Figure 10: Waterfall plot with cross-coupled stiffness.

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 1

Import 1 (imp1)

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 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 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 1/s	Angular speed of the rotor

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 α_{dM} text field, type `6.04`.

4 In the β_{dK} text field, type `2e-6`.

First Support 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Solid Rotor (rotsld)>Rotor Axis 1** 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, under **Component 1 (comp1)>Solid Rotor (rotsld)** 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 Material: Turbine

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

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

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

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

Applied Force 1

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

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

3 Specify the **F** vector as

0	x
0	y
1e3	z

Rigid Material: Compressor

1 In the **Model Builder** window, right-click **Rigid Material: Turbine** and choose **Duplicate**.

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

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

4 Select Domain 2 only.

Applied Force 1

1 In the **Model Builder** window, expand the **Rigid Material: Compressor** node, then click **Applied Force 1**.

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

3 Specify the **F** vector as

1e3	x
0	y
0	z

MESH 1

Swept 1

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 1

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

Size 1

1 In the **Model Builder** window, right-click **Swept 1** 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 1

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(0,5000,100000)	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. In the associated text field, type 9.

4 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 **2009.5+19.004i**.

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.

1. In the **Model Builder** window, click **Whirl (rotsld)**.
2. In the **Settings** window for **3D Plot Group**, locate the **Data** section.
3. From the **Eigenfrequency (Hz)** list, choose **2228.1-306.44i**.

Whirl 1

1. In the **Model Builder** window, expand the **Whirl (rotsld)** node, then click **Whirl 1**.
2. In the **Settings** window for **Whirl**, locate the **Coloring and Style** section.
3. In the **Number of planes** text field, type `1`.
4. In the **Number of rings** text field, type `20`.
5. Click **Change Color Table**.
6. In the **Color Table** dialog box, select **Thermal>HeatCamera** in the tree.
7. Click **OK**.
8. Click the **Zoom Extents** button in the **Graphics** toolbar.
9. In the **Whirl (rotsld)** toolbar, click **Plot**.
10. Click **Plot**.

    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.

11. In the **Home** toolbar, click **Add Predefined Plot**.

ADD PREDEFINED PLOT

1. Go to the **Add Predefined Plot** window.
2. In the tree, select **Study 1/Parametric Solutions 1 (sol2)>Solid Rotor>Campbell Plot, Fixed Frame (rotsld)**.
3. Click **Add Plot** in the window toolbar.
4. In the **Home** toolbar, click **Add Predefined Plot**.

RESULTS

Campbell Plot, Fixed Frame (rotsld)

1. In the **Model Builder** window, under **Results** click **Campbell Plot, Fixed Frame (rotsld)**.

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

2 In the **Settings** window for **1D 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 Click the **Show Legends** button in the **Graphics** toolbar.

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.Ovg`.

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 From the **Width** list, choose **2**.

9 Find the **Line markers** subsection. From the **Marker** list, choose **Circle**.

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

11 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 **1D 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 Click the **Play** button in the **Graphics** toolbar.

ROOT

Eigenfrequency Analysis is finished now. Now you will analyze the harmonic response of the turbocharger due to external 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(100,100,3000)`.

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(2e3,2e3,1e5)`	`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 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Prism** in the tree.

6 Click **OK**.

7 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 1

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 (sol46)**.

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 1**.

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 `abs(u)`.

6 Locate the **x-Axis Data** section. In the **Expression** text field, type `Ow`.

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

8 Locate the **Coloring and Style** section. Click **Change Color Table**.

9 In the **Color Table** dialog box, select **Rainbow>Prism** in the tree.

10 Click **OK**.

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

12 In the **Waterfall plot** toolbar, click **Plot**.

13 Click the **Scene Light** button in the **Graphics** toolbar.

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

14 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, under **Results>Waterfall plot** 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 Click the **Play** button in the **Graphics** toolbar.