# MADYN 2000 Version 4.6

The main new feature in version 4.6 is the **Axial Fluid Film Bearing**.

Besides that, further features and improvements were introduced as described in this document.

The new version is compatible with WINDOWS 11.

**Table of content for detailed description of new features and improvements**

# 1. Axial Fluid Film Bearing AFB

Axial fluid film bearings are included in the module for radial fluid film bearings.

## 1.1 Overview, Analysis Types, Bearing Types, Oil Supply Conditions

An axial fluid film bearing AFB normally has 2 oil films to carry loads in either direction. They must be modelled as 2 different bearings. In figure 1.1 a system with an axial bearing (2 oil films) is shown.

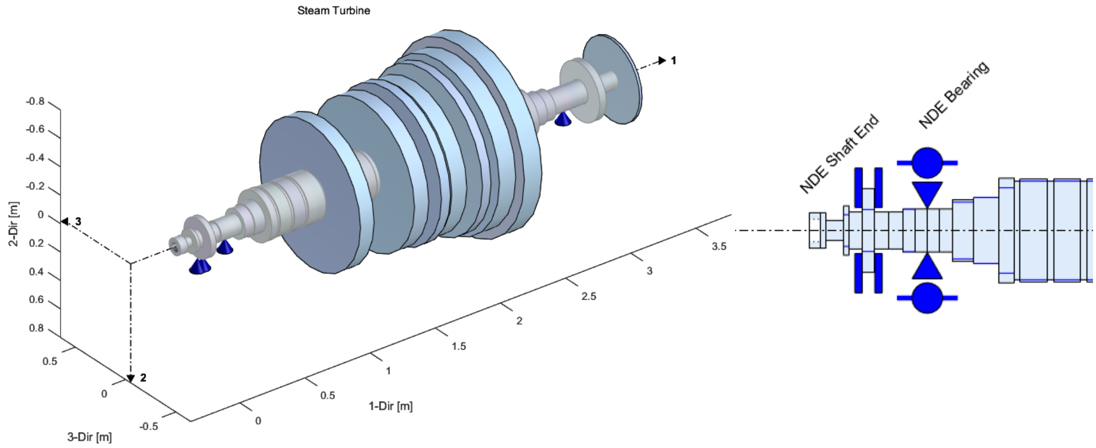



Fig. 1.1: System with AFBs (2 oil films), shaft plot with the symbol for AFBs

For each bearing the location of the oil film with respect to the station, where it is mounted, must be defined as right side or left side of the station. Each of the 2 bearings for each oil film has a reference gap. The sum of two gaps corresponds to the movability of the shaft in axial direction (total axial clearance). In figure 1.3 in the next chapter the GUI with the edit fields for these inputs can be seen.

The properties of an AFB depend on the load and speed. The affected coordinates are the displacements in axial 1 and radial 2,3 directions x1, x2, x3 and the rotations about the radial 2,3 axes $\Phi 2$, $\Phi 3$ (see coordinate system in figure 1.1).

Axial fluid film bearing data cannot be imported in dimensioned or dimensionless form as radial fluid film bearing data. Only the option corresponding to a user defined radial fluid bearing RFB is available, i.e. the geometry must be completely defined and the bearing is calculated accordingly.

The following options exist for the calculation:

- Analysis type c_ad, constant adiabatic
- Analysis type v_ad, variable adiabatic

The following bearing types are available in MADYN 2000 (also see figure 1.2):

- Fixed pad bearings without Land Area
- Fixed pad bearings with Constant Taper Angle
- Fixed pad bearings with Constant Taper Length
- Tilting Pad with Line Support
- Circular Tilting Pad (has line support)

The meanings of the analysis types are like those for the radial fluid film bearing. Turbulence is considered and for tilting pad bearings optionally thermo-elasticity, whereas the consideration of 2-phase flow in the cavitation zones currently is not possible.

The tapers of fixed pad bearings can be sealed. The taper then resembles a hydrodynamic pocket as it can be modelled for radial fluid film bearings.

The following oil supply conditions can be defined for all bearing types:

- Pocket Pressure
- Supply Pressure (the pressure before an orifice, corresponding to direct lubrication of a radial fluid film bearing)
- Defined Flow (similar to unsealed defined flow for radial fluid film bearing)

The same lubricants as for radial fluid film bearings are available (oil types with different viscosity, water, user defined fluids).

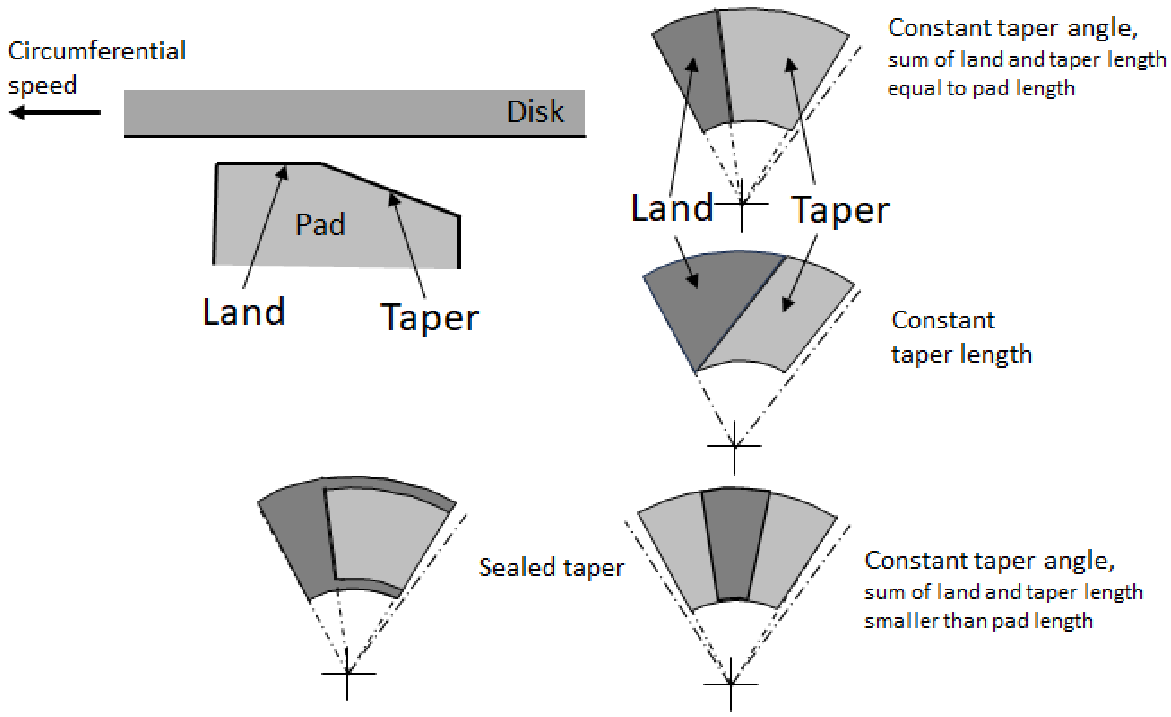



Fig. 1.2: Explanations different fixed pad bearings

### 1.2 Definition

The GUI to define an axial bearing for fixed pad bearings is shown in figure 1.3 and for tilting pad bearings in figure 1.4. Currently only symmetric bearings are available. Hereby the middle of the first pad is always aligned with the 2-direction of the MADYN 2000 global coordinate system (see figure 1.5).

The fixed pad bearing GUI is shown for a bearing with land and constant taper angle (see figure 1.2). The land and taper lengths are input as angles. For constant taper length (instead constant angle) the taper angle applies to the mean diameter of the pad.

Fixed pads with constant angle can have a sealed taper as shown in figure 1.2. For constant length the taper cannot be sealed.

In case the sum of land angle and taper angle is smaller than the pad angle, both sides of the pad have a taper as indicated in figure 1.2, thus yielding a geometry suited for rotation in both directions.

Tilting pad bearings can have a manufactured curvature instead of a taper. The pivot of the tilting pads can have an offset. The input fields for both can be seen in figure 1.4. The definition of the curvature in units for length can be seen in figure 1.6.

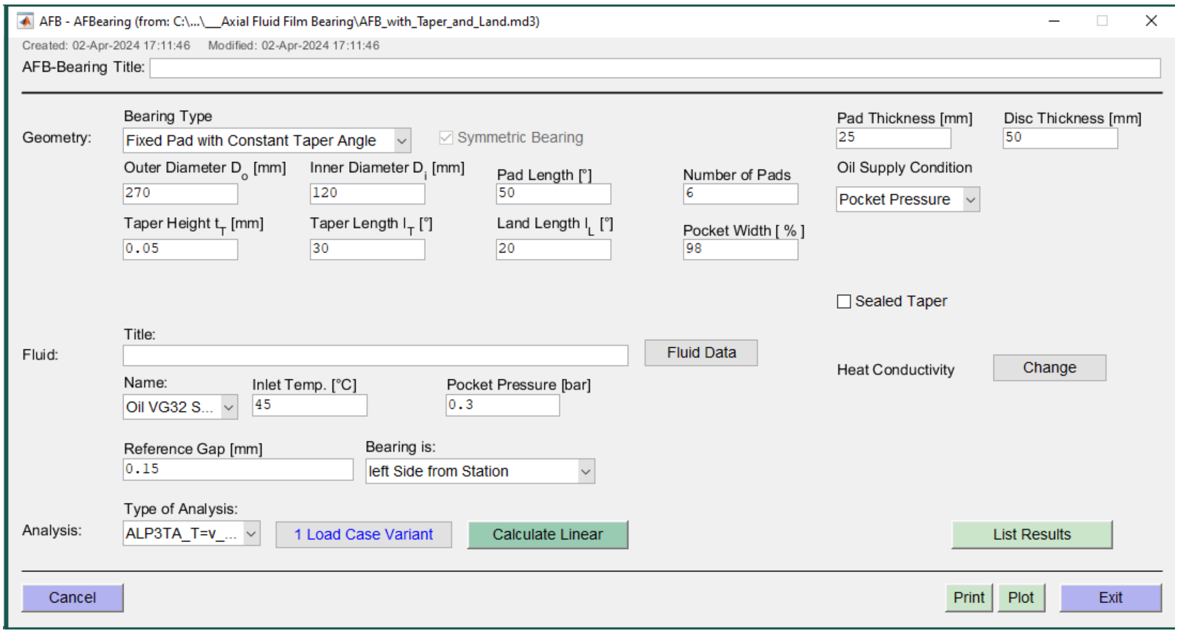



Fig. 1.3: GUI for the definition of a fixed pad bearing with land and constant taper angle

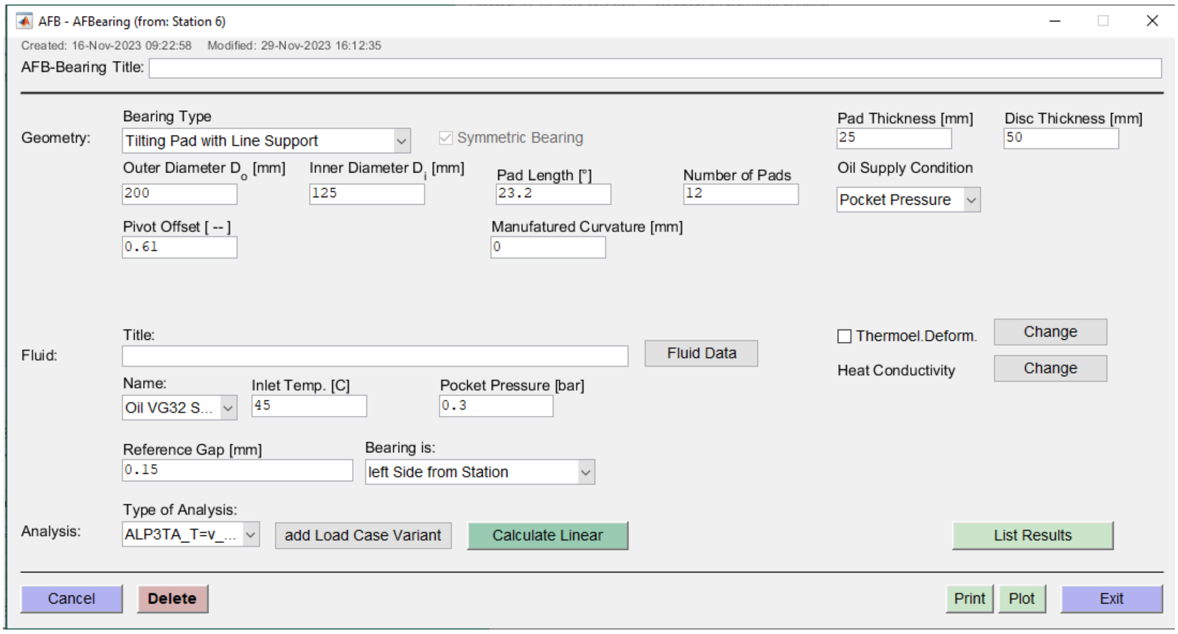



Fig. 1.4: GUI for the definition of a tilting pad bearing

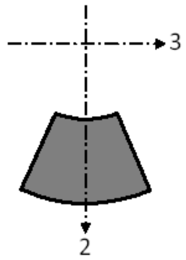



Fig. 1.5: Position of the 1st pad of a symmetrical bearing in the global MADYN 2000 coordinate system

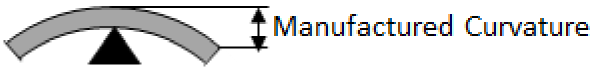



Fig. 1.6: Definition of Manufactured Curvature for tilting pad bearings

The MADYN 2000 plot of the pad geometry is shown in figure 1.7 for the fixed pad bearing defined in the GUI in figure 1.3. Only one pad is shown, since only symmetric bearings can currently be modelled.

In the geometry plot the following reference heights are used:

- For a fixed pad bearing: Taper height $t_T$, i.e. 50μm for the current bearing
- For tilting pad bearings: Mean pad radius / 1000

The minimum clearance in the plot corresponds to these reference heights.

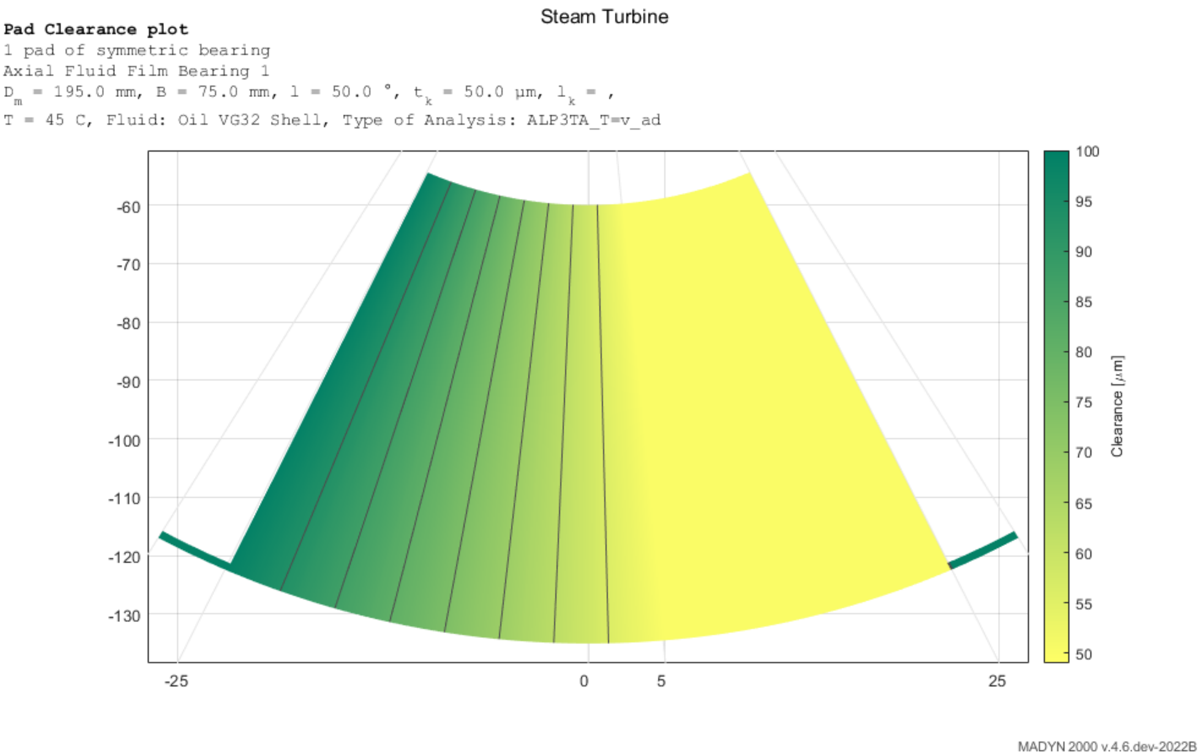



Fig. 1.7: Geometry plot of a fixed pad bearing with land and taper

### 1.3 Bearing Loads, Analyses and Results

Loads for an AFB are defined by an axial force and tilting angles about the radial axes (rotation Φ2, Φ3). The definition is in the global coordinate system of MADYN 2000, i.e. the tilting is defined as an angle about the 2- and 3-direction (coordinate 5 and 6).

The loads can be defined as load variants directly in the AFB GUI as for radial fluid film bearings and the analysis of the linearised characteristics of the bearing for a perturbation about the static equilibrium is started by the “Calculate Linear” button. The results are then stored in the AFB object. The GUI to define the load variant is shown in figure 1.8. The loads are summarised in a list and the mean bearing pressure due to the axial force is additionally shown. It is calculated using the complete carrying pad areas (land and convergent taper).

Alternatively, the load of an axial bearing may stem from a static analysis as the loads for radial bearings. The linearised characteristics are then calculated when required for the analyses (eigenvalues EIG, Campbell diagram CDG, harmonic response HAR, also see chapter 1.5). The speeds for which the linear characteristics are calculated are the same as those for radial fluid film bearings without Sommerfeld similarity (see table II.6.6 in chapter II.6.12 in the MADYN 2000 documentation). Sommerfeld similarity is not applicable, because the AFB properties do not only depend on a dimensionless load, but also on the tilting of the bearing. Once the characteristics are calculated they are stored as load variants in the AFB object.

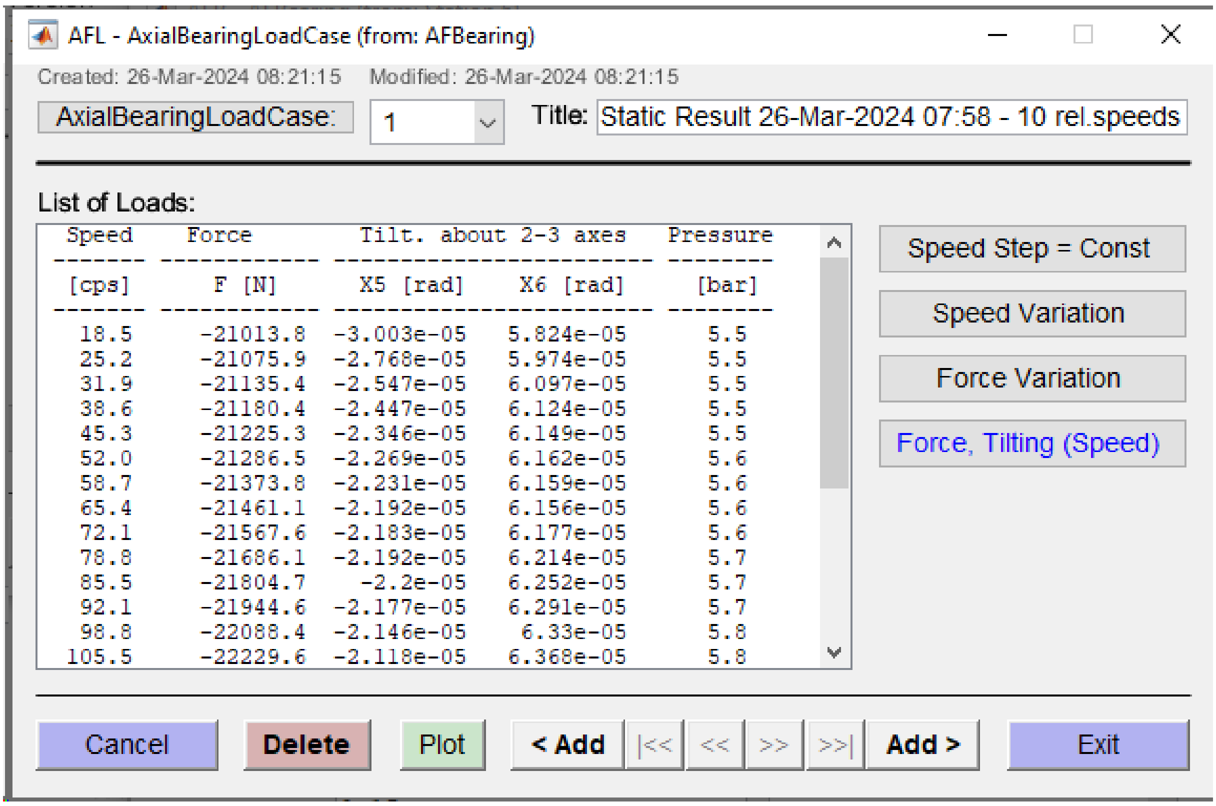



Fig. 1.8: Definition of a load variant for an AFB

Results of a load variant can be listed and plotted with “List Results” button. A print with the inputs and the main results can be invoked from the “Print” button.

The linear characteristics are a 5x5 stiffness and damping matrix for the coordinates 1,2,3,5,6 as for the stiffness of rolling element bearings. Under “List Results” only the main coefficients $k_{11}$, $k_{55}$, $k_{66}$ and $d_{11}$, $d_{55}$, $d_{66}$ are shown. The complete 5x5 matrices can be seen in the prints of analyses EIG, CDG and HAR (see figure 1.17).

The loads and the resulting static equilibrium position can be shown in a plot (see figure 1.9). It is invoked from the window opened by “List Results”.

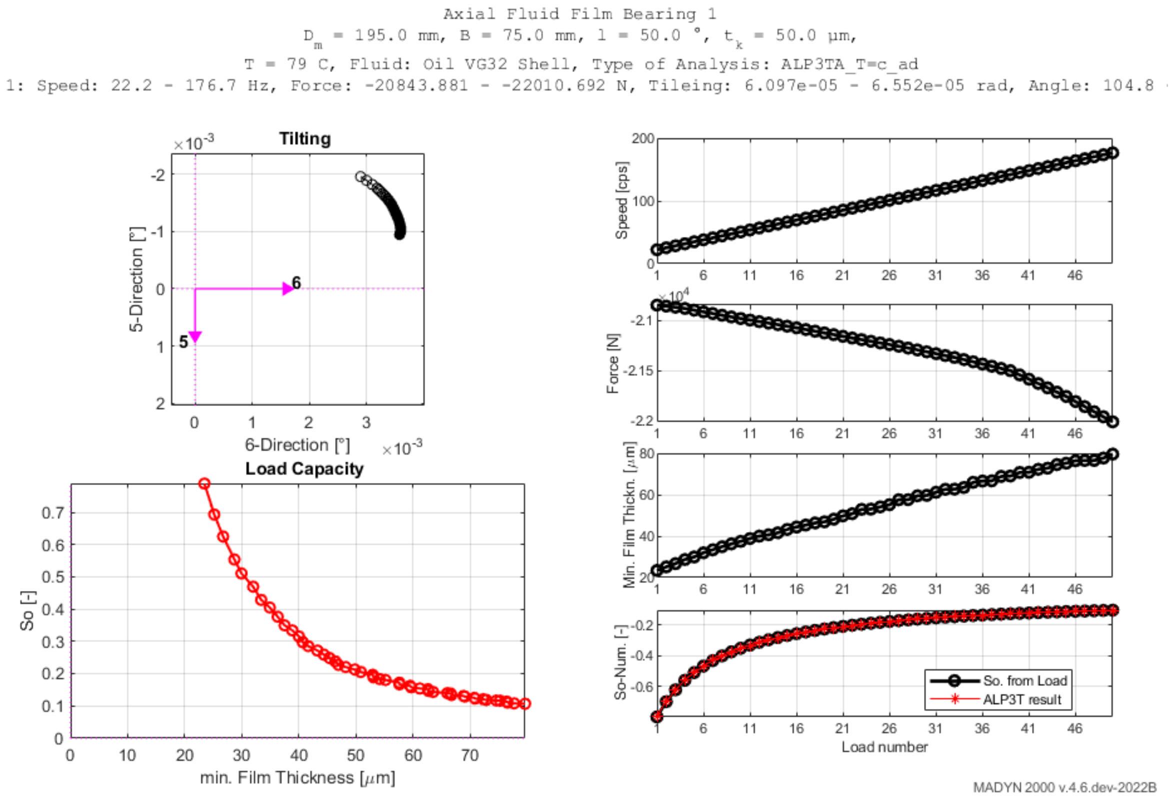



Fig. 1.9: Plot summarising the load and the static equilibrium

As for radial fluid film bearings the Sommerfeld numbers calculated from the load according to the load variant (either directly input or from a EIG, CDG, HAR analysis) are shown (black circles) as well as those from the iterated equilibrium points (red stars). In case there is noticeable deviation the analysis has not converged.

The So-number of an axial bearing hereby is defined as follows:

$$So = \frac{p_{mean}\, h}{\eta\, \Omega\, r_m} \qquad (1.1)$$

with $p_{mean}$ as the mean pressure calculated from the axial load and the total carrying pad areas (land and convergent taper), $h$ as a reference clearance (taper height for fixed pad bearings, $r_m/1000$ for tilting pad bearings), $r_m$ as the mean pad radius calculated from the inner and outer radius, $\eta$ as the viscosity at the inlet temperature and $\Omega$ as the speed in rad/s.

Field plots for the clearance in operation, temperatures, pressures and other results can be plotted. These plots can be invoked from the window opened by “List Results” by selecting a speed and load (similar to the field plots for radial fluid bearings). An example for a bearing with taper and no land is shown in figure 1.10.

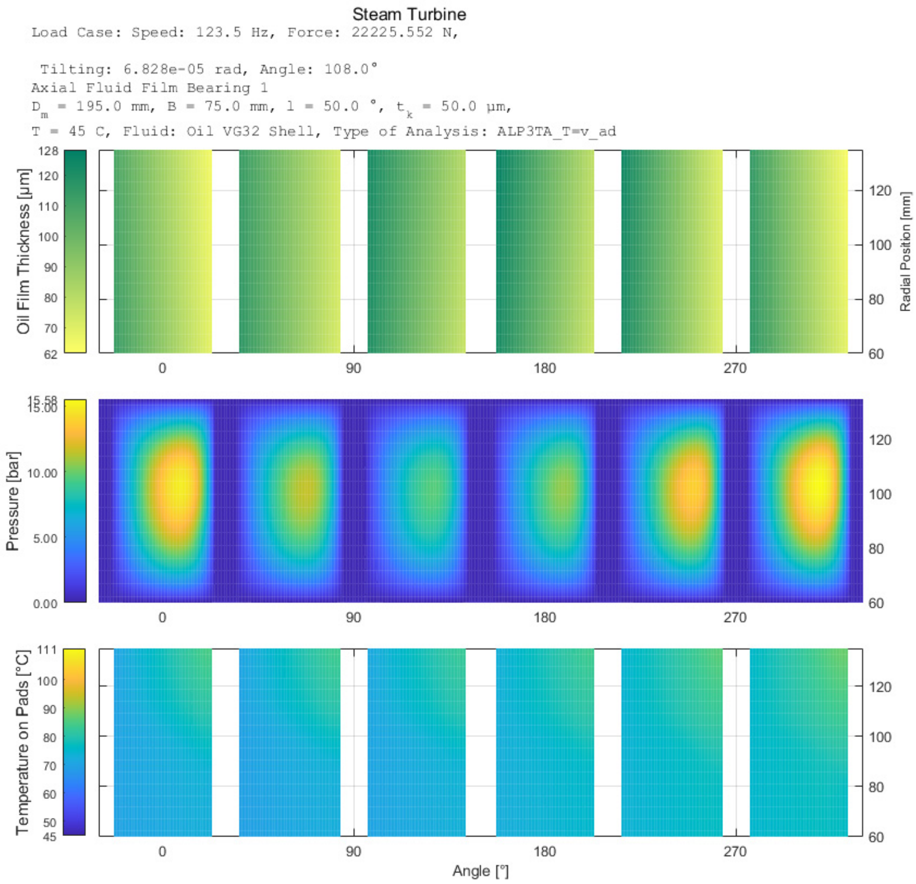



Fig. 1.10: 2D field plots of an axial fluid film bearing

### 1.4 Special Properties of AFBs to be Observed

<u>Pure lateral systems</u>

In pure lateral systems AFBs are ignored, although they might have an influence mainly because of the rotational stiffness about the radial axes.

<u>Static analysis with rigid supports</u>

The axial bearing is assumed as rigid in axial direction and as free for the rotation about the radial axes for a static analysis with rigid bearings.

Systems with AFDs must be statically determined in axial direction to carry out such an analysis, since only then the resulting axial bearing load is reasonable assuming rigid bearings. This is fulfilled in systems with one axial bearing and one rotor or several rotors, which are axially rigidly connected or connected with a stiffness.

One axial bearing with two oil films is modelled in MADYN 2000 by two bearings, which makes the system statically overdetermined. Therefore, the check for static determination is carried out separately for the left and right oil films. Only the loaded bearing of the 2 bearings is subsequently used in the analyses with rigid bearings.

### 1.5 Analyses of Systems with AFB

As described above, the AFB can be modelled and analysed as a standalone object. Analyses are carried out with load variants defined in the AFB GUI. This is useful for designing an axial bearing.

In case an AFB is part of a system, the bearing is calculated on demand if needed in analyses such as EIG (eigenvalue analysis), CDG (Campbell diagram) or HAR (harmonic response). The load is then defined in the GUI of the analysis, either by direct load input or by selecting a static analysis, in which the loads were calculated. The analysis GUI for a Campbell diagram with the controls to define the bearing loads is shown in figure 1.11.

Alternatively, the bearing properties can be precalculated by starting the analysis from the AFB GUI. However, for AFBs mounted in a system this is less useful than for RFBs, since AFB properties depend on a tilting angle, which is part of the AFB load and not known beforehand. Moreover, Sommerfeld similarity does not apply for the same reason.

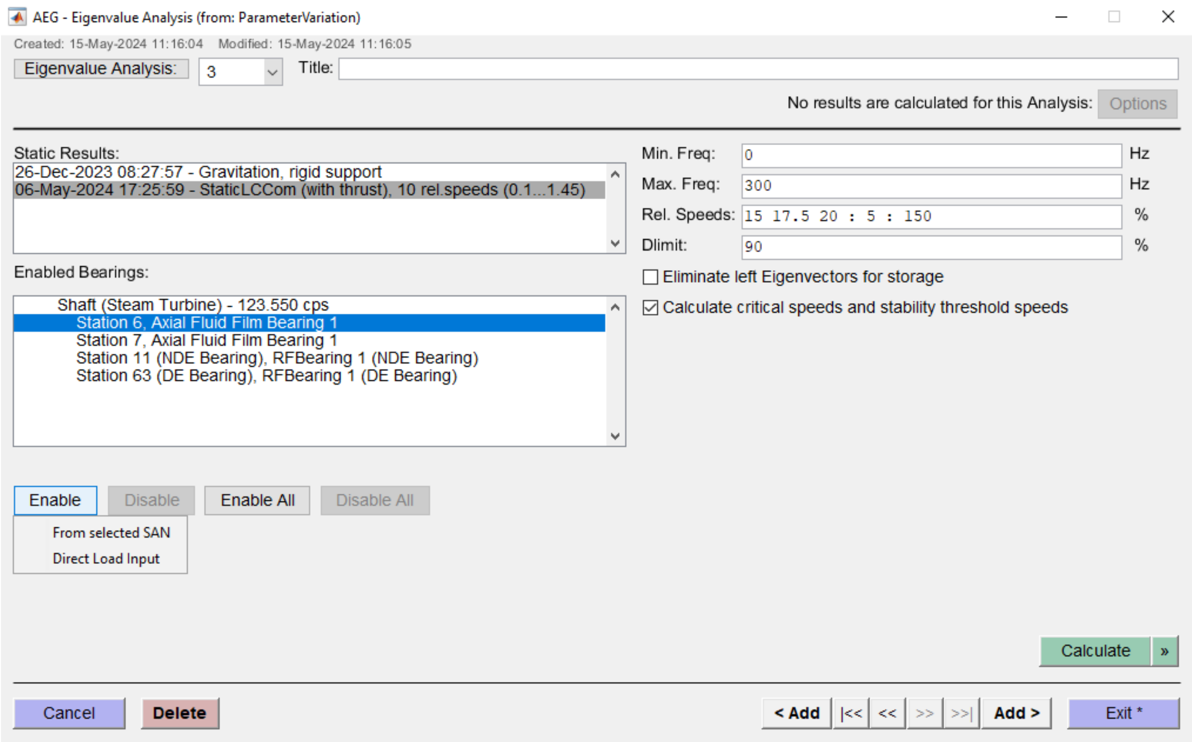



Fig. 1.11: Campbell diagram analysis GUI, with options to define bearing loads

A system with AFBs in general is statically overdetermined, even for a simple rotor on 2 radial bearings, due to the tilting forces of the axial bearing on the rotor. This does not apply for static analyses of pure lateral systems or with rigid bearings, for which the assumptions mentioned in chapter 1.4 apply.

The static loads of the system in figure 1.1 are shown in figure 1.12. The corresponding deformation at nominal speed can be seen in figure 1.13 and the forces in figure 1.14.

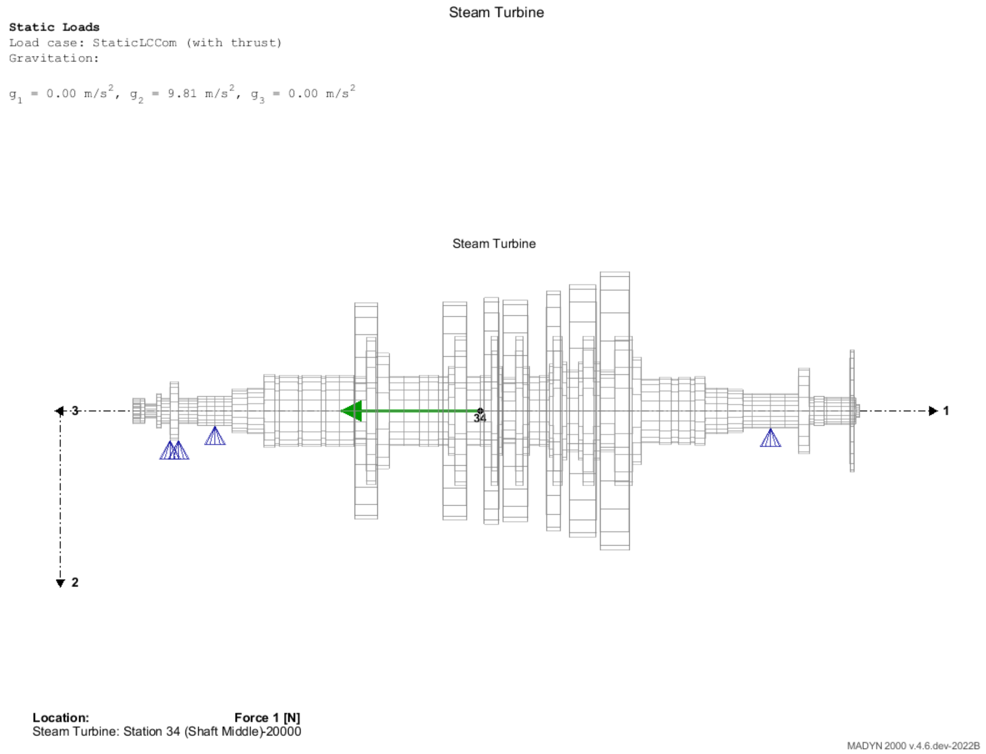



Fig. 1.12: Static load, weight and axial force

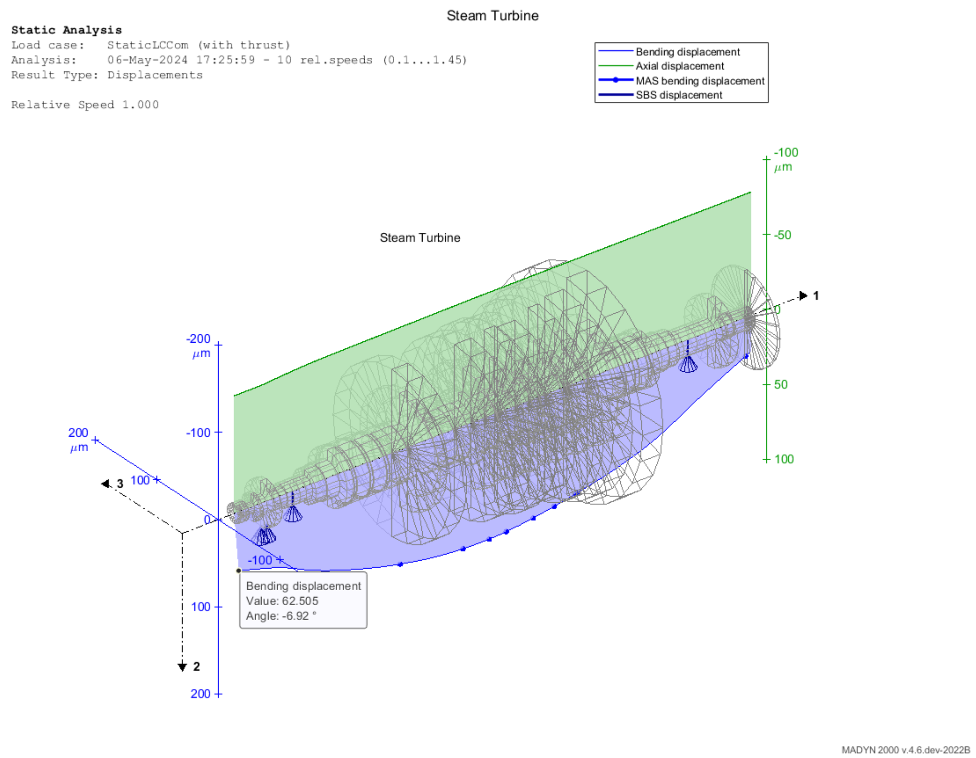



Fig. 1.13: Static deformation at nominal speed

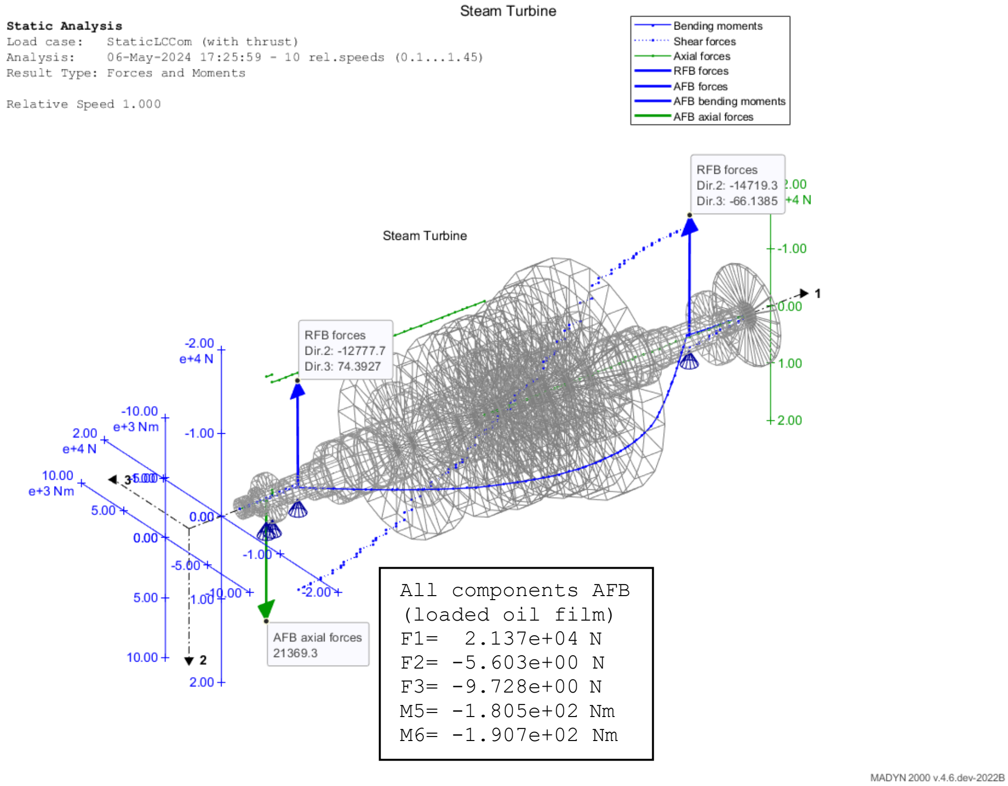
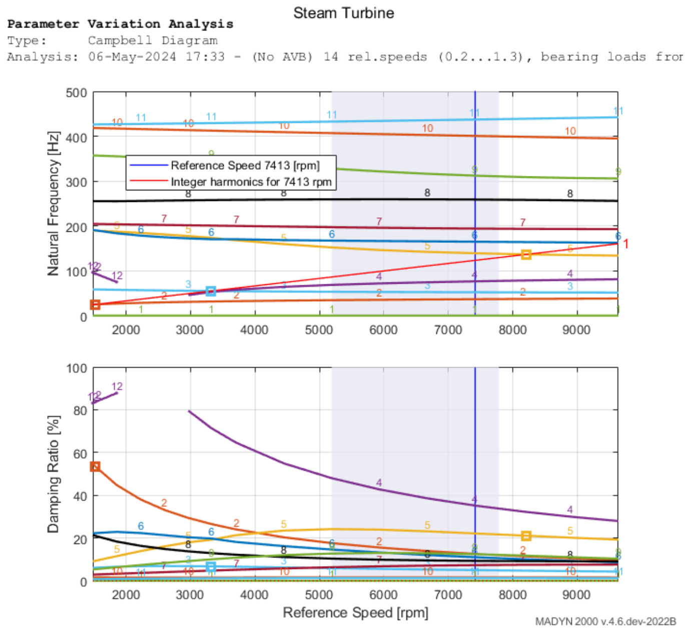



Fig. 1.14: Static forces at nominal speed

As can be seen in figure 1.13 the deformation has a component in horizontal direction, which is caused by the axial bearing. For this rotor supported on radial tilting pad bearings it would not exist without it. In figure 1.14 the forces are shown, including the bearing forces on the rotor. The bending displacement in negative 3 direction of the rotor on the left side is caused by the negative moment M5 of the AFB on the rotor, due to the hydrodynamic pressure of the oil film caused by the tilted axial bearing disk. A bending moment M6 arises for the same reason. Additionally, there are force components in the radial 2,3 directions mainly caused by oil friction. The axial force of the loaded axial bearing oil film is higher than the applied axial force of 20’000N, because the unloaded oil film of the axial bearing exerts an additional load.

A Campbell diagram of the rotor with and without axial bearing is shown in figure 1.15 and 1.16. A comparison of the two diagrams shows, that the modes up to mode 7 are not influenced much by the axial bearing, except, that the new highly damped axial mode 3 appears. It is slightly coupled to lateral vibrations. In the diagram without axial bearing the axial mode is mode 1, which is a free rigid body mode with frequency zero. The frequency and damping of bending modes above mode 7 are influenced by the AFB, they both increase due to the tilting of the axial bearing disk.

The linearised axial bearing stiffness and damping matrix at the nominal speed of 7’413rpm about the static equilibrium position according to figures 1.13 and 1.14 are shown in figure 1.17. It can be seen that all coordinates are coupled and non-zero, except torsion (coordinate 4).



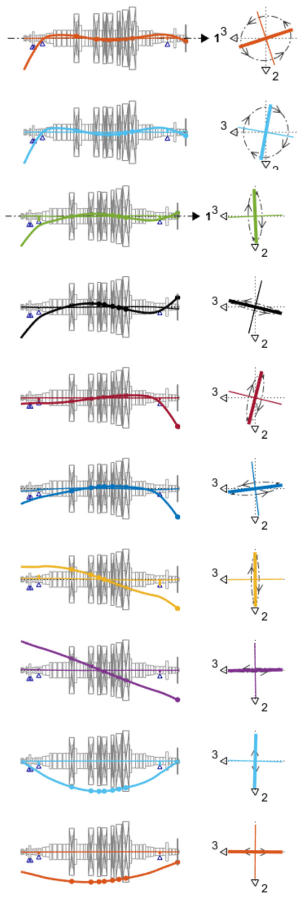
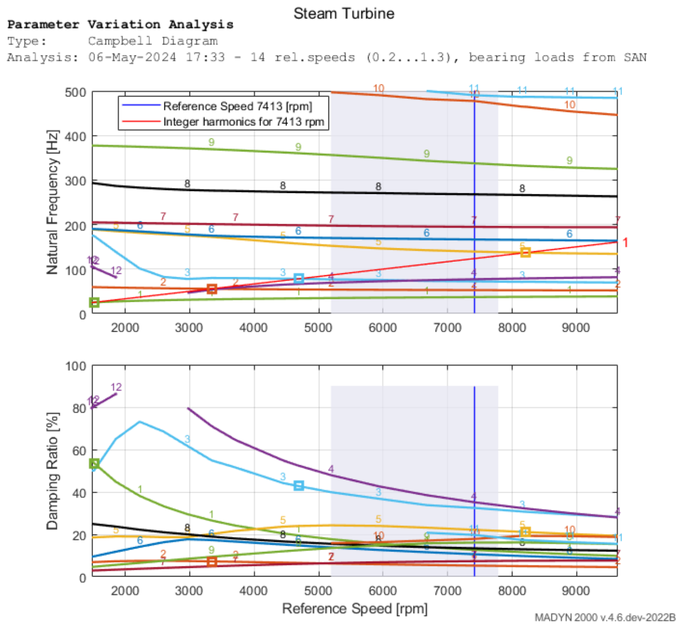



Fig. 1.15: Campbell diagram with mode shapes
at nominal speed without AFB



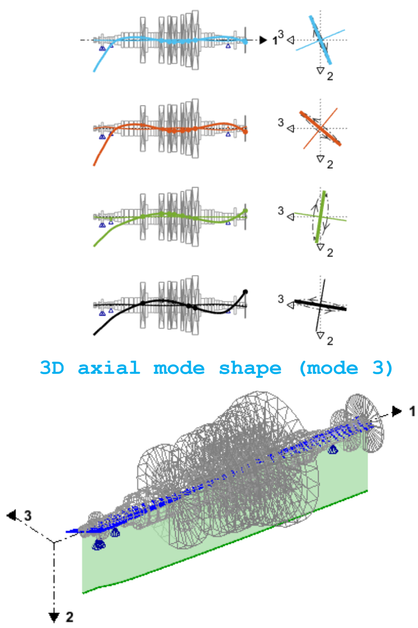




Fig. 1.16: Campbell diagram with mode shapes influenced by the AFB
at nominal speed with AFB

Station 6, General Stiffness Matrix (speed 7413 rpm):

| | k1 | k2 | k3 | k4 | k5 | k6 |
|---|---|---|---|---|---|---|
| | [1/m] | [1/m] | [1/m] | [1/rad] | [1/rad] | [1/rad] |
| [N] | 6.8317e+08 | 13542.2942 | -42865.9228 | 0 | 8.0796e+06 | -6.5258e+06 |
| [N] | 3927.2305 | 0.1740 | -0.2820 | 0 | 1650.3552 | 30.9449 |
| [N] | -3255.2454 | -0.1904 | 0.2449 | 0 | -18.9292 | 1667.0344 |
| [N m] | 0 | 0 | 0 | 0 | 0 | 0 |
| [N m] | 7.8837e+06 | 350.6898 | -572.0046 | 0 | 3.3000e+06 | 58075.9940 |
| [N m] | -6.5052e+06 | -385.0150 | 491.9928 | 0 | -39926.2349 | 3.3303e+06 |

Station 6, General Damping Matrix (speed 7413 rpm):

| | d1 | d2 | d3 | d4 | d5 | d6 |
|---|---|---|---|---|---|---|
| | [1/m] | [1/m] | [1/m] | [1/rad] | [1/rad] | [1/rad] |
| [N s] | 9.7651e+05 | 19.0719 | -61.8725 | 0 | 9404.6154 | -2861.8546 |
| [N s] | 4.5912 | 1.3389e-04 | -3.1210e-04 | 0 | 2.3997 | 0.0340 |
| [N s] | -1.3887 | -1.7065e-04 | 1.3408e-04 | 0 | 0.0341 | 2.4391 |
| [N s m] | 0 | 0 | 0 | 0 | 0 | 0 |
| [N s m] | 9301.7532 | 0.2729 | -0.6392 | 0 | 4833.6316 | 66.1106 |
| [N s m] | -2817.7128 | -0.3486 | 0.2736 | 0 | 66.2739 | 4911.4770 |

Fig. 1.17: Stiffness and damping matrix of the AFB at 7’413rpm

## 2. Configurable Plots, New Features for Harmonic Response Plots

The configurable plots for harmonic response results have been extended by some features, which were only available for standard plots until now: resonance peak evaluations and the possibility to plot bending results for radial directions defined by the user.

The GUI to configure the plots is shown in figure 2.1. User defined bending direction can be defined by activation the check box “Bending Options”. The GUI to define them is shown in figure 2.2.

The different evaluations are available for the following analyses and results:

1. Basic peak evaluation, i.e. determining the amplification factor by the half power width:
   HAR analyses : Synchronous, non-synchronous resonance plots
   Result types: Forces, displacements, velocities, accelerations
   Projections: Bending major
   Bending 2-direction, 3-direction or any other user defined direction 2’,3’
   Bending rotational major
   Bending rotational 5-direction (about 2), 6-direction (about 3)
   Axial
   Torsion
   See figure 2.3 for a non-synchronous resonance plot in user defined direction 2’.

2. Peak evaluation according to API-617 7th edition, API-684:
   HAR analyses: Synchronous resonance plots
   Result types: Displacements
   Projections: Bending major
   Bending 2-direction, 3-direction or any other defined direction
   See figure 2.4 for a synchronous resonance plot in user defined direction 2’.

3. Peak evaluation according to API-617 8th edition:
   Same analyses and projections as point 2.
   See figure 2.5 for a synchronous resonance plot in user defined direction 2’.

Details to the evaluations according to API can be found in /2/, /3/ and /4/

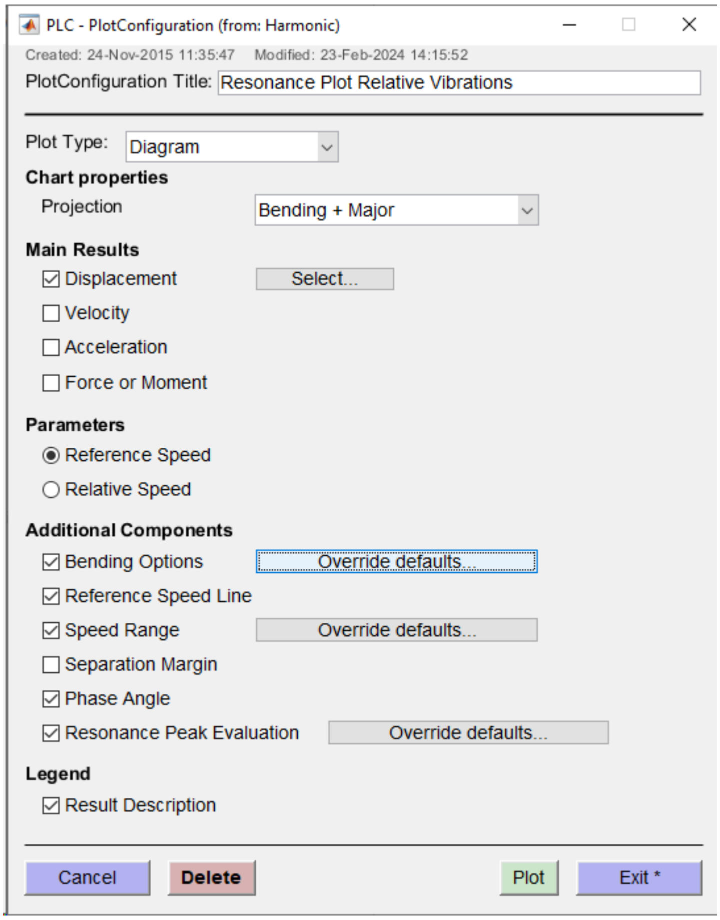



Fig. 2.1: GUI to configure plots for harmonic response

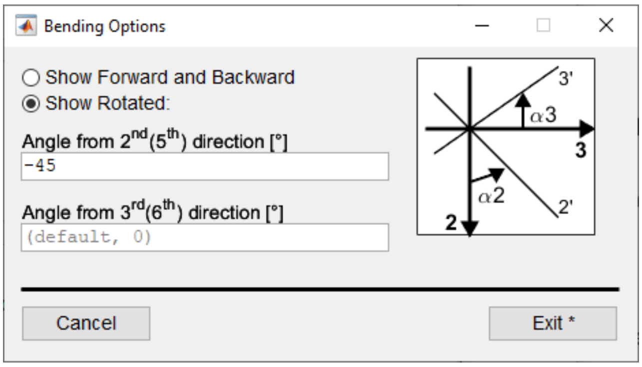



Fig. 2.2: GUI to define user defined directions (bending options)

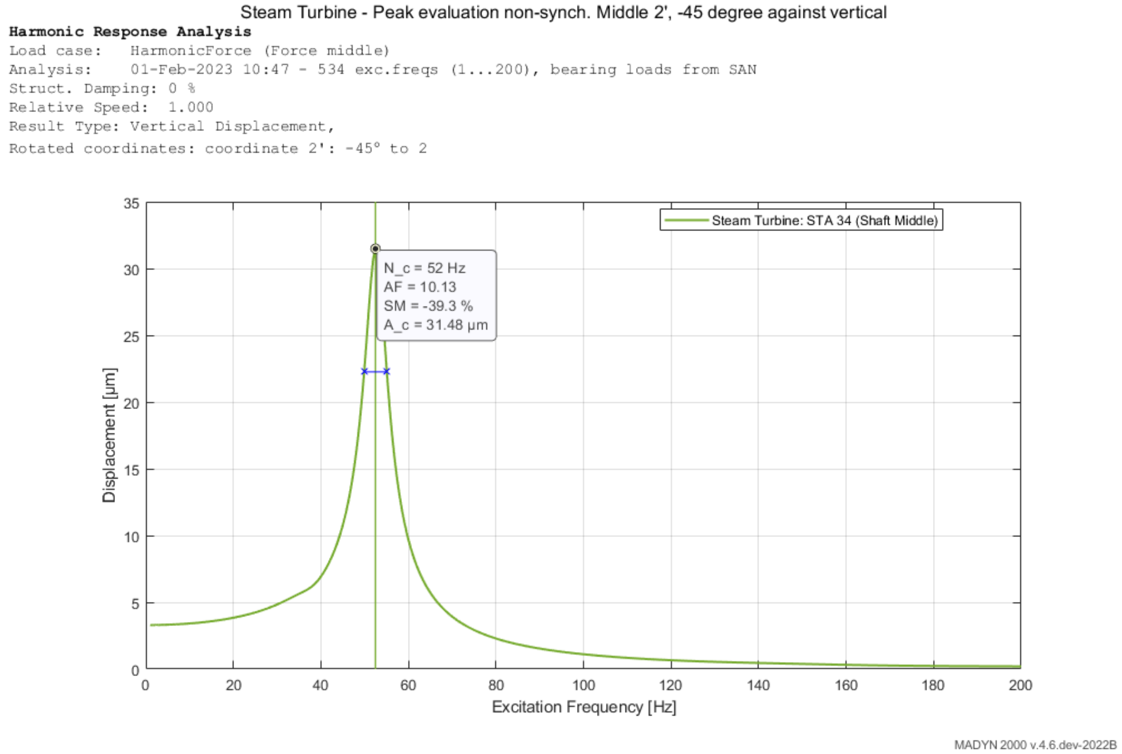



Fig. 2.3: Basic resonance peak evaluation

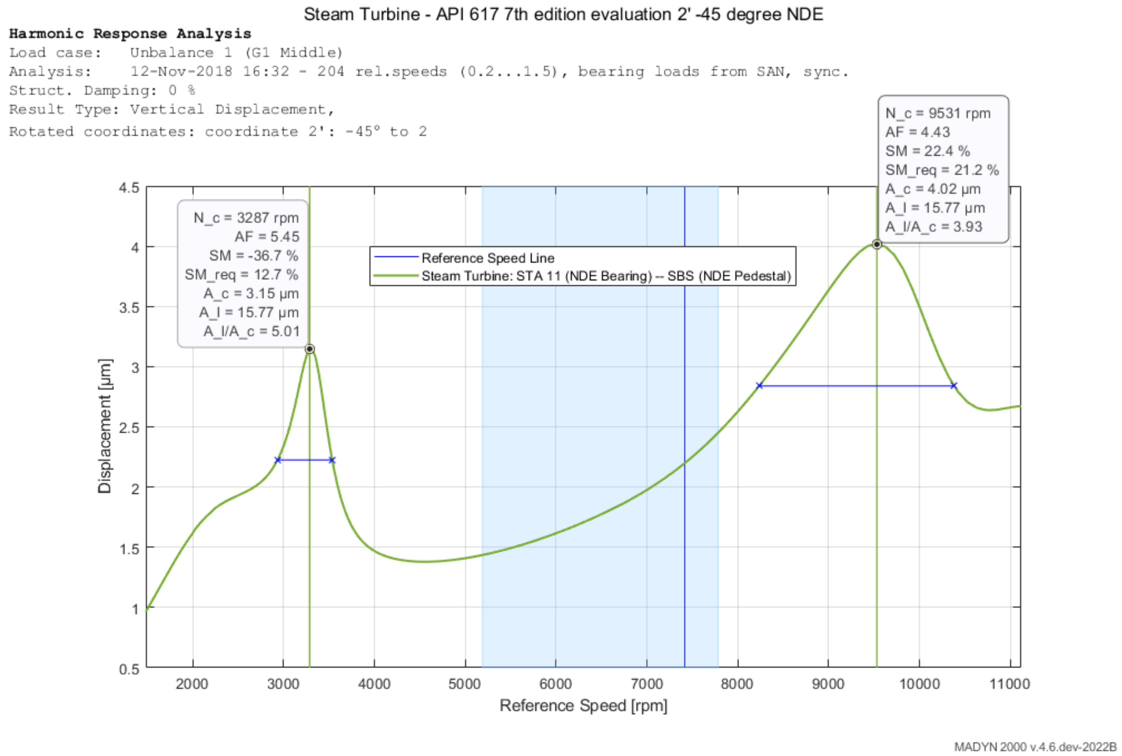



Fig. 2.4: Resonance peak evaluation according to API-684, API 617-7$^{th}$ edition

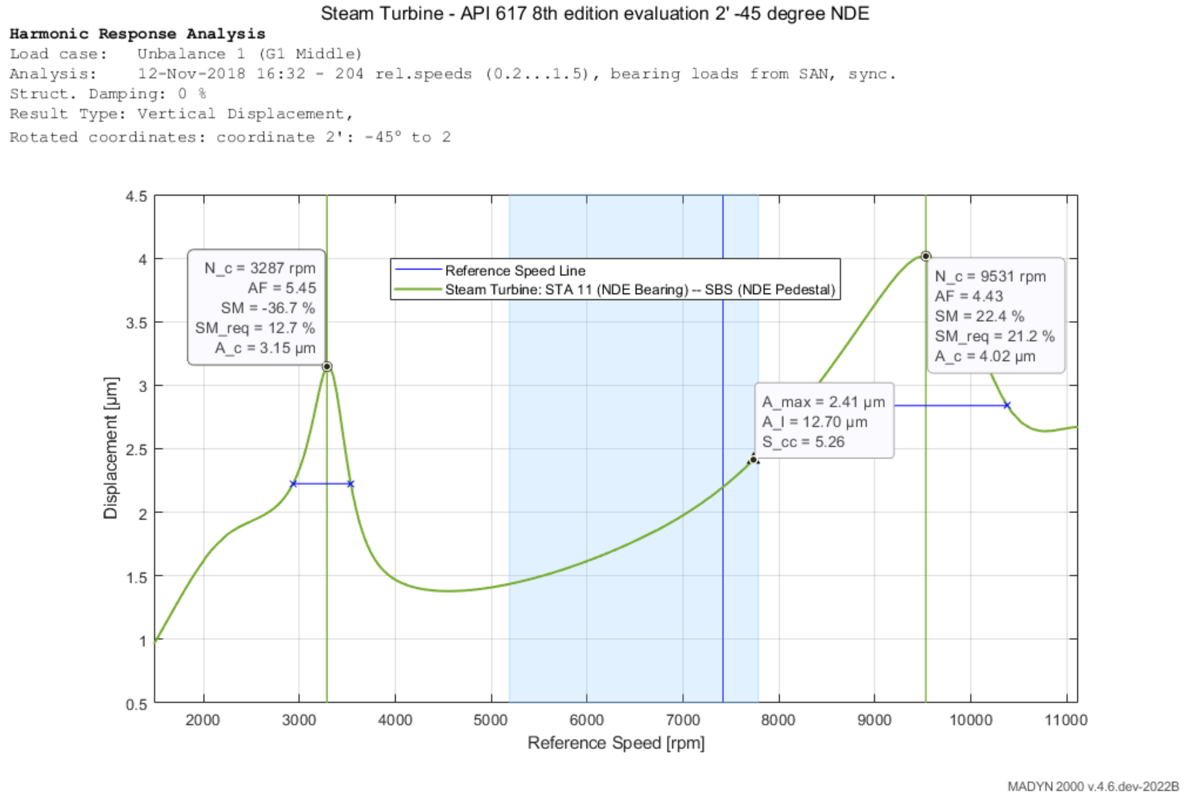



Fig. 2.5: Resonance peak evaluation according to API 617 8[th] edition

# 3. Improvements for Analyses with Fluid Film Bearings

## 3.1 Dealing with Numerical Issues

The analyses of fluid film bearings can be very complex, especially for “variable adiabatic” analyses, which allow to consider many effects such as

- 3D temperature distribution (requiring the solution of the energy equation),
- 2-phase flow for cavitation,
- turbulence,
- thermo-elastic deformations,
- oil supply conditions.

For this reason, convergence can be an issue, especially in cases where the bearing has a physical problem, i.e. would not function well in the real world (overloaded bearing, tilting pad bearings with centre pivot and small preload => fluttering, extremely high speeds). The problem of too high speed can often occur because standards such as API require analyses up to 150% maximum speed, a speed, which a real machine will never see.

Iterations in the bearing analysis have been continuously improved. In version 4.6 further improvements especially for the tilting angle of tilting pad bearings were introduced.

Should non-convergence still occur, the following measures were introduced in version 4.6 to mitigate the consequences:

- Restart the analysis in case of non-convergence with different initial conditions. This is applied for iterations to find the static equilibrium as well as for the analyses of rotordynamic coefficients. 3 attempts are performed to get convergence.
- In case convergence can still not be achieved, not converged results are ignored for the interpolation of the rotordynamic bearing coefficients. This measure is promising, since in most cases only for a few speeds of all the calculated speeds for a harmonic response or Campbell diagram analyses do not converge.

### 3.2 Enabling, Disabling Fluid Film Bearing and Defining their Loads in Analyses

In analyses such as EIG, HAR and CDG fluid film bearings can be enabled or disabled. For enabled bearings static loads can be defined. They can be either directly input or taken from the results of a static analysis. The analysis GUI with this selection for a Campbell diagram analysis is shown in figure 1.11.

In version 4.6 this selection can be done for individual bearings RFBs and AFBs. In previous versions either of the two possible bearing load origins (direct input / static analyses results) applied for all bearings.

In case the load is directly input, the bearing is marked with an “F” (force input), in case it stems from a static analysis result it is marked with a “S”.

### 3.3 Analysis Type DIN with Qp

Until version 4.5 $p_{in}$ was only used to determine the additional pocket side flow $Q_p$. It had no influence on the dimensionless characteristics of the bearing. In version 4.6 it is used as real inlet pressure in the hydrostatic pocket and thus influences the dimensionless characteristic. It is a dependency and results are deleted in case the inlet pressure is changed.

## 4. Improvements for Rolling Element Bearings

New rolling element bearing types are available in version 4.6. The new complete list of types with their boundary conditions is shown in table 4.1.

Moreover, the print invoked from the REB object GUI has been improved.

Table 4.1: Bearing types and their boundary conditions (loads they can take)

| | Bearing Type | Boundary Conditions |
|---|---|---|
| 1 | Deep groove ball bearing | Load in radial and axial direction |
| 2 | Deep groove ball bearing (double row) | Load in radial and axial direction |
| 3 | Axial deep groove ball bearing | Load in radial and axial direction |
| 4 | Angular contact ball bearing | Load in radial and axial direction* |
| 5 | Axial angular contact bearing | Load in radial and axial direction |
| 6 | Angular contact bearing (double row) | Load in radial and axial direction |
| 7 | Axial angular contact bearing (double row) | Load in radial and axial direction |
| 8 | Self aligning ball bearing | Load in radial and axial direction (no moment) |
| 9 | Self aligning ball bearing (double row) | Load in radial and axial direction (no moment) |
| 10 | Four point ball bearing (radial) | Load in radial and axial direction |
| 11 | Four point ball bearing (axial) | Load in radial and axial direction |
| 12 | Three point ball bearing (split inner ring) | Load in radial and axial direction |
| 13 | Three point ball bearing (split outer ring) | Load in radial and axial direction |
| 14 | Duplex bearings | Load in radial and axial direction |
| 15 | Cylindrical roller bearing | Load in radial direction only. Types with shoulder also in axial direction. |
| 16 | Cylindrical roller bearing (double row) | Load in radial direction only. Types with shoulder also in axial direction. |
| 17 | Axial cylindrical roller bearing | Load in axial direction only |
| 18 | Axial cylindrical roller bearing (double row) | Load in axial direction only |
| 19 | Needle bearing | Load in radial direction only |
| 20 | Tapered roller bearing | Load in radial and axial direction* |
| 21 | Tapered roller bearing (double row) | Load in radial and axial direction* |
| 22 | Axial tapered roller bearing | Load in radial and axial direction |
| 23 | Barrel roller bearing | Load in radial and axial direction |
| 24 | Toroidal roller bearing | Load in radial and axial direction |
| 25 | Spherical roller bearing | Load in radial and axial direction |
| 26 | Half radial spherical roller bearing | Load in radial and axial direction* |
| 27 | Axial spherical roller bearing | Load in radial and axial direction |
| 28 | Cross roller bearing (radial) | Load in radial and axial direction |
| 29 | Cross roller bearing (axial) | Load in radial and axial direction |
| 30 | Angular roller bearing (radial) | Load in radial and axial direction |
| 31 | Angular roller bearing (axial) | Load in radial and axial direction |

* Bearing requiring axial load, although it is mainly radial

# 5. Improvements in Static Analyses Iterations

For the displacement iteration in nonlinear static analyses as they are necessary for statically overdetermined systems when considering the oil film in the fluid film bearings or the deformation in rolling element bearings a relaxation factor is introduced. In cases of non-convergence, it can be reduced. Its non-existence in previous versions for the displacement iteration is equivalent to a relaxation factor of 1. The new default value is 0.5.

# 6. Changes due to MATLAB Update

## 6.1 Submenus

Some submenus are now called differently than in previous versions. They have a special controls button next to the buttons or edit fields.

In figure 6.1 the submenu for the selection of units is shown. Previously they were selected with a left mouse click on the unit shown above the edit field.

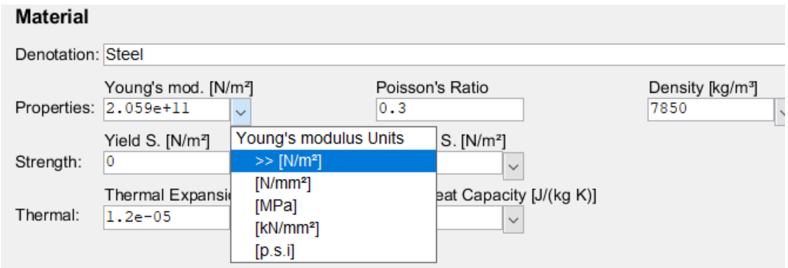



Fig. 6.1: Menu for unit selection

In figure 6.2 the submenu for plots is shown. Previously the submenu was opened with a left mouse click on the plot button.

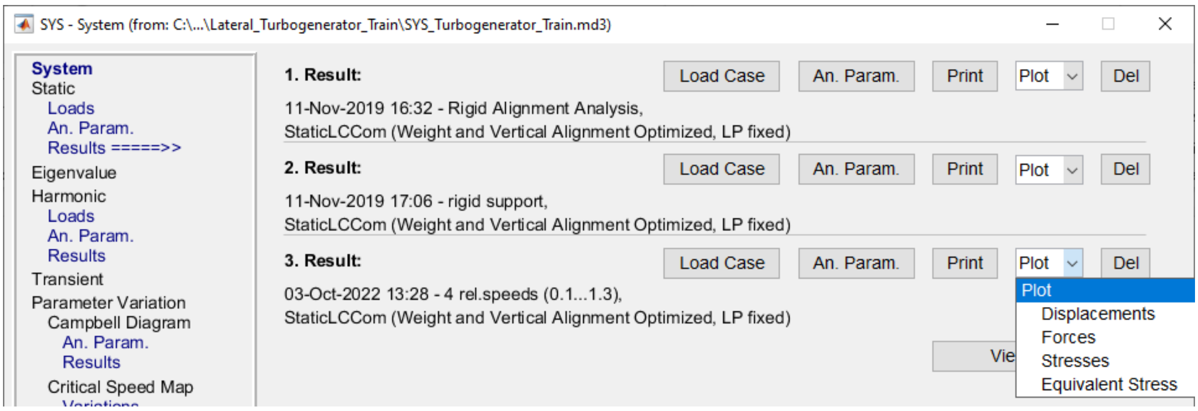



Fig. 6.2: Menu for selection of plot results

### 6.2 Special Features of Plots

Some controls of features described in the MADYN 2000 documentation in chapter I.10.2 “Special Features of Plots” can no longer be found in the tool bar of plot windows.

They can now be activated by moving the cursor to the upper edge of axes (see figure 6.3 and 6.4) and clicking on a specific symbol. The meaning of the symbols for diagrams and 2D plots are as follows (from left to right in figure 6.3):

Saving Copying | Data Tips | Pan | Zoom in | Zoom Out | Restore View

For 3D shape plots the meaning of the data tips are (from left to right in figure 6.4):

Saving Copying | Brush Data | Data Tips | Rotate | Pan | Zoom in | Zoom Out | Restore View

In figure 6.3 “Data Tips” is activated, in figure 6.4 “Rotate”.

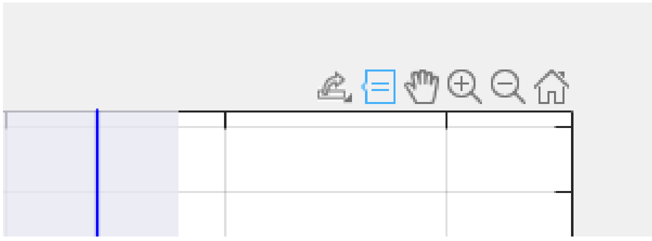


Fig. 6.3: Features for axes in diagram and shape plots

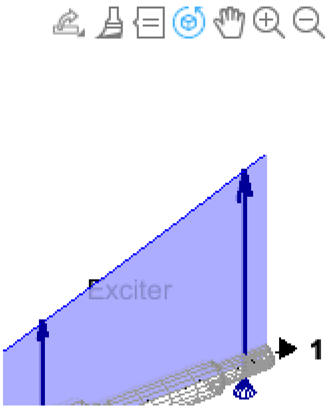



Fig. 6.4: Features for axes in 3D plots

## 6. References

/1/ MADYN 2000 Documentation version 4.6, June 2024

/2/ API (American Petroleum Institute) Recommended Practice 684

/3/ API (American Petroleum Institute) Standard 617: Axial and Centrifugal Compressors and Expander-compressors for the Petroleum Chemical and Gas Industry, 7th Edition

/4/ API (American Petroleum Institute) Standard 617: Axial and Centrifugal Compressors and Expander-compressors for the Petroleum Chemical and Gas Industry, 8th Edition