



- 1 -

## MADYN 2000 Version 4.4

The following new features and improvements were introduced in version 4.4:

1. [New Harmonic Loads and Analysis Types](#)
2. [New Features for Active Systems \(Magnetic Bearings\)](#)
3. [New Features and Improvements for Fluid Film Bearings](#)
4. [Improvements for Squeeze Film Dampers](#)
5. [New Interfaces](#)
6. [Further Improvements](#)

Table of content for detailed description of features:

|                                                                                                |    |
|------------------------------------------------------------------------------------------------|----|
| 1. Harmonic Loads and Analysis Types .....                                                     | 2  |
| 1.1 Unbalance Moments and Tilted Disks .....                                                   | 2  |
| 1.2 New Synchronous Excitations (Bent Shaft, Parallel and Angular Offset).....                 | 3  |
| 1.3 New Non-Synchronous Excitations (Speed Multiples, Integer and Non-Integer Harmonics) ..... | 7  |
| 1.4 Load Case Combinations .....                                                               | 10 |
| 1.5 Balancing .....                                                                            | 12 |
| 2. Active Systems (Magnetic Bearings).....                                                     | 16 |
| 2.1 Import of State Space Controllers.....                                                     | 16 |
| 2.2 Export of Modally Reduced Rotor State Space Systems .....                                  | 17 |
| 2.3 Export of Controllers .....                                                                | 19 |
| 3. Fluid Film Bearings .....                                                                   | 19 |
| 3.1 Bearing Data in Analyses .....                                                             | 19 |
| 3.2 Field Plots of Results .....                                                               | 21 |
| 3.3 Axial Thermo-Elastic Pad Deformation for Tilting Pad Bearings .....                        | 23 |
| 3.4 Asymmetric Pockets .....                                                                   | 25 |
| 3.5 Boundary Condition for Direct Lubrication of Tilting Pad Bearings .....                    | 26 |
| 3.6 Temperature Outputs in Print .....                                                         | 27 |
| 3.7 Hydrostatic Pockets .....                                                                  | 27 |
| 4. Squeeze Film Dampers .....                                                                  | 28 |
| 5. Interfaces .....                                                                            | 29 |
| 5.1 Import of Dynamic Bearing Supports from ANSYS .....                                        | 29 |
| 5.2 Import of CAD Files.....                                                                   | 31 |
| 6. Further Improvements .....                                                                  | 32 |
| 6.1 Gear Springs .....                                                                         | 32 |
| 6.2 Shaft Plots.....                                                                           | 32 |



## 1. Harmonic Loads and Analysis Types

### 1.1 Unbalance Moments and Tilted Disks

In version 4.4 unbalance moments or moments caused by tilted disks can directly be defined as loads. The corresponding edit fields are activated by the radio button “Define Unbalance and Unbalance Moment” (see figure 1.1).

In case the unbalance is applied to a disk the moment can be expressed as a disk tilt angle. The relation between tilt angle and moment is according to equation 1.1, with  $I_t$  and  $I_p$  as the transverse and polar moment of inertia of the disk.

$$\alpha = \frac{U_M}{I_t - I_p} \quad (1.1)$$

A disk is characterised by the fact, that all inertia properties (mass, polar and transverse moment of inertia) are defined. In the GUI only such masses appear apart from the masses with an offset.

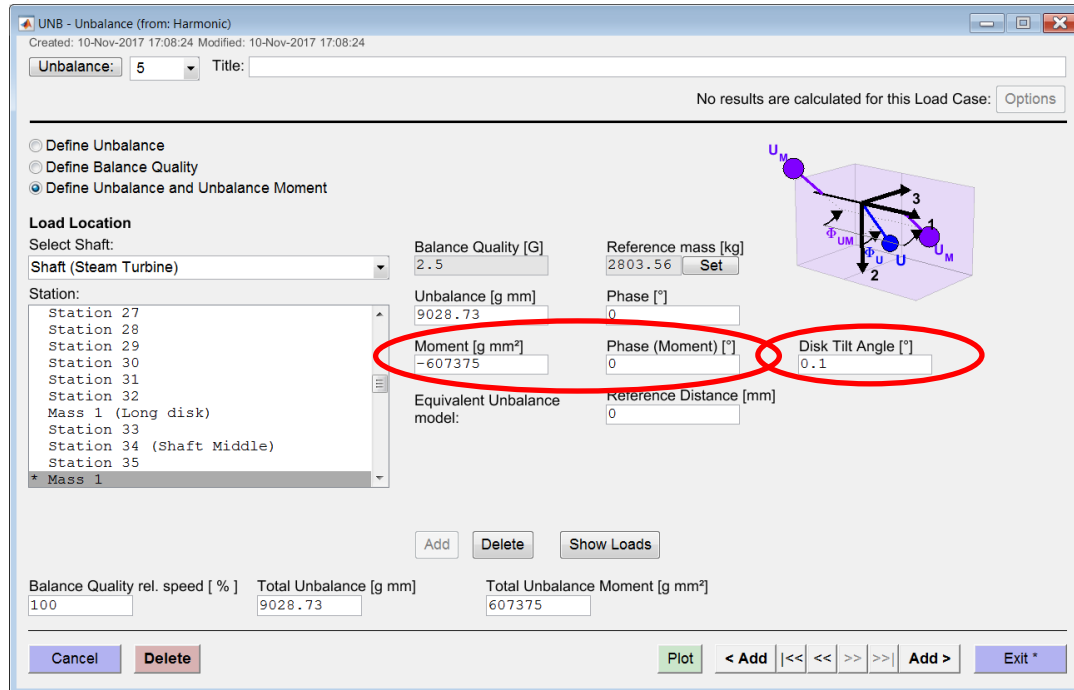


Fig. 1.1: Definition of an unbalance and unbalance moment

In case a reference distance  $L$  for the moment is given, the unbalance and unbalance moment are transformed according to equations 1.2 and 1.3 to two unbalances in plane I and II with this distance. The corresponding GUI is shown in figure 1.2 with edit fields for the unbalances in the two planes.

$$\hat{U}_I = \frac{1}{2} \left( \hat{U} - \frac{\hat{U}_M}{L} \right) \quad (1.2)$$

$$\hat{U}_{II} = \frac{1}{2} \left( \hat{U} + \frac{\hat{U}_M}{L} \right) \quad (1.3)$$



- 3 -

Fig. 1.2: GUI to define an unbalance moment with reference distance

In case the  $\hat{U}_I$  and  $\hat{U}_{II}$  have been determined the balancing quality considering both unbalances according to the following formula is shown in the GUI.

$$G = \frac{|\hat{U}_I| + |\hat{U}_{II}|}{m_{ref}} \Omega \quad (1.4)$$

Without the distance the G value corresponds to the unbalance without the unbalance moment.

## 1.2 New Synchronous Excitations (Bent Shaft, Parallel and Angular Offset)

Apart from unbalance and force excitation the following new load cases are available in version 4.4.

A **bent shaft** is defined by two nodes, a maximum displacement between the two nodes caused by the bending and a phase angle for the direction of the maximum displacement. Phase angle zero means, that the lateral displacement between the nodes is in 2-direction. The GUI to define the load is shown in figure 1.3. The load plots are shown in figure 1.4 as shape and forces. The load shape plot visualises the bent shaft for slow rotation with lateral displacement zero at the two nodes for the bending definition. The shape is shown at the instant zero and a quarter period later. The force plot illustrates the bending moments applied at the two nodes to realize the specified bending.



- 4 -

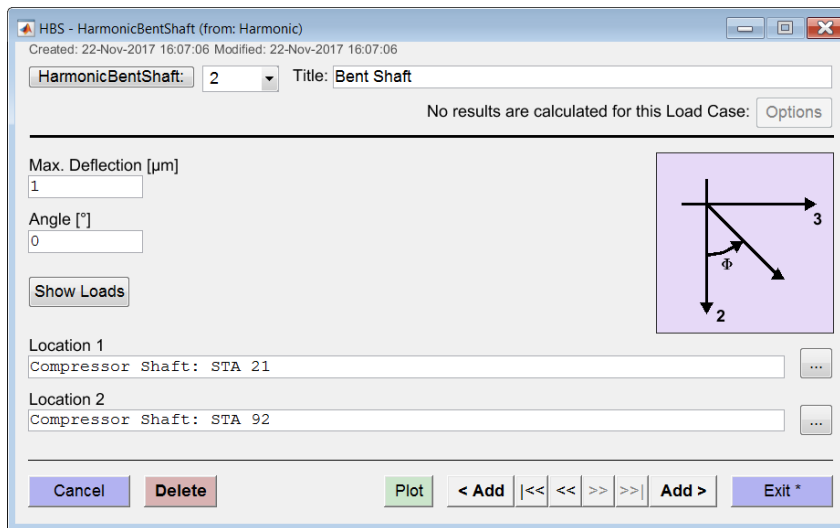


Fig. 1.3: GUI to define a bent shaft

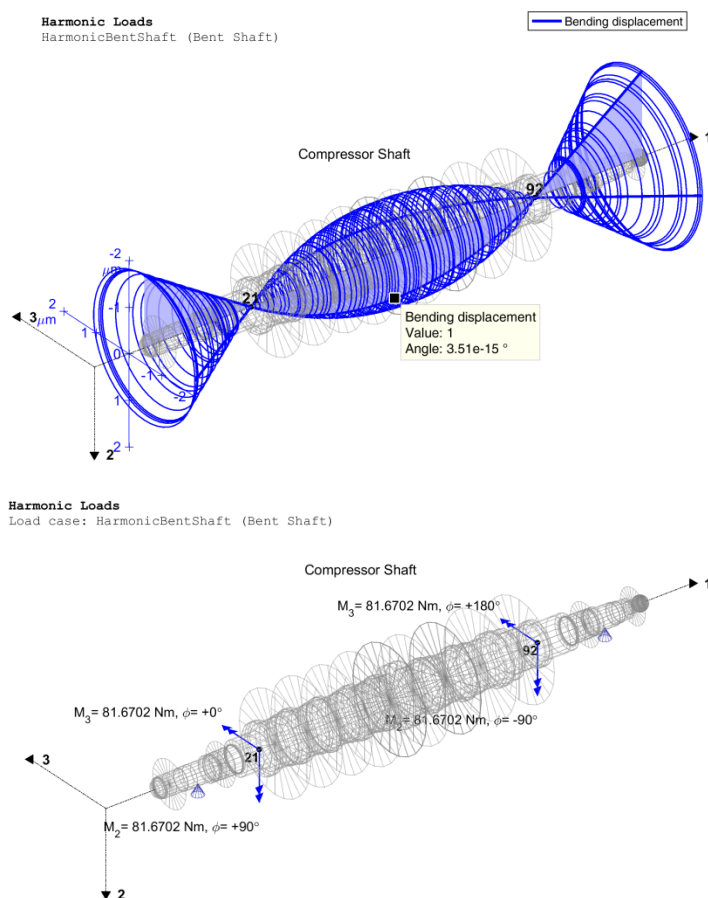


Fig. 1.4: Plots for the visualisation of a bent shaft (shape and forces)



- 5 -

An **angular offset** is defined by two nodes, an angle between two nodes and a phase angle for the direction of the offset. Phase angle zero means, that the lateral displacement caused by the offset is in 2-direction. The GUI to define the load is shown in figure 1.5. The offset angle can be defined directly or by a diameter and an axial displacement across the diameter. The load plots are shown in figure IV.4.6 as shape and forces. The load shape plot visualises the deformed shaft for slow rotation clamped at location 1. The shape is shown at for instant zero and a quarter period later. The force plot illustrates the bending moments applied at the two nodes to realize the specified angular offset.

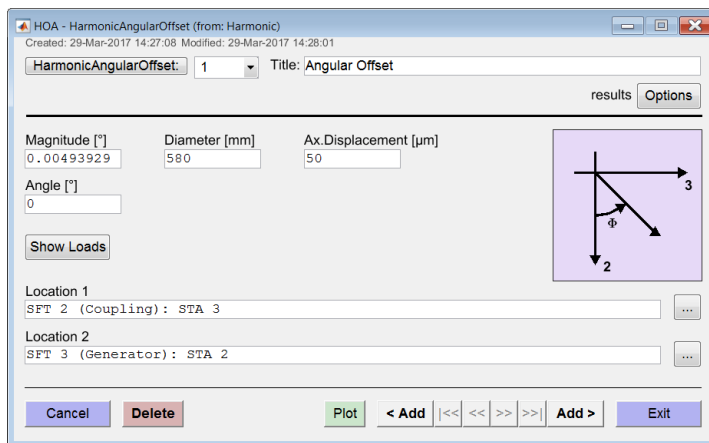


Fig. 1.5: GUI to define an angular offset

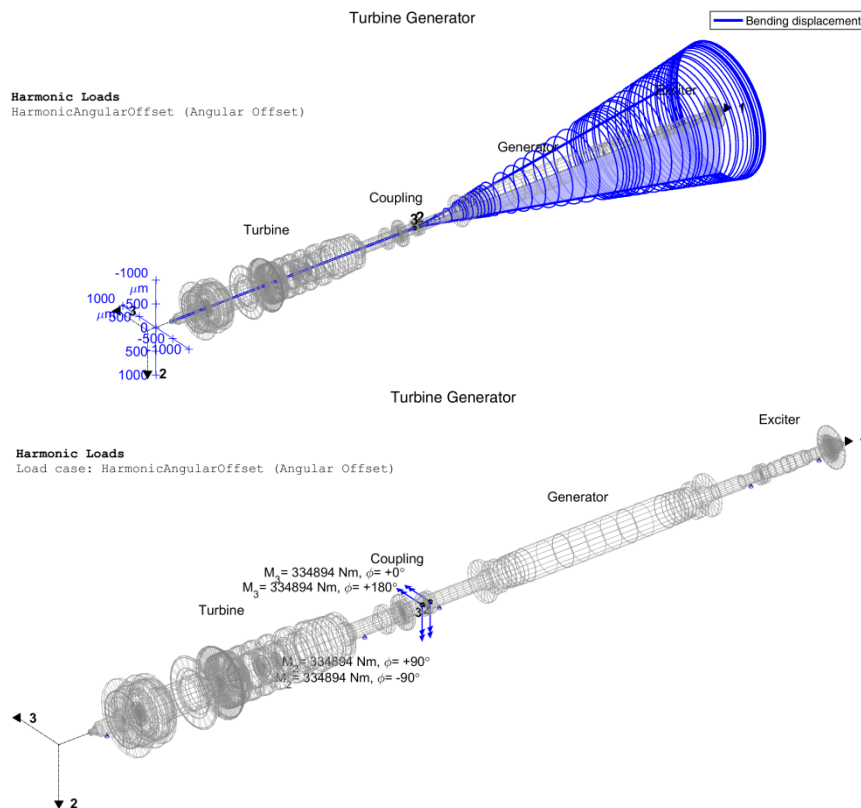


Fig. 1.6: Plots for the visualisation of an angular offset (shape and forces)



- 6 -

A **parallel offset** is defined by two nodes, an offset value and a phase angle for the direction of the offset. Phase angle zero means, that the lateral displacement caused by the offset is in 2-direction. The GUI to define the load is shown in figure Fig. IV.4.7. The load is visualised as shown in figure IV.4.8 in a similar manner as the angular offset.

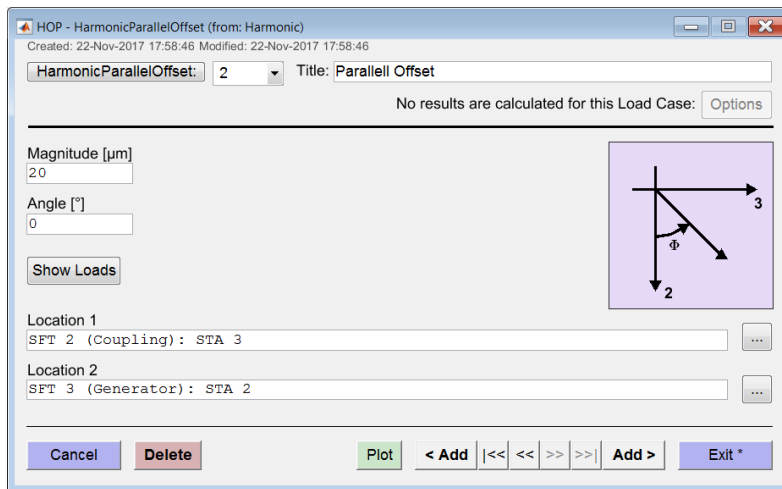


Fig. 1.7: GUI to define a parallel offset

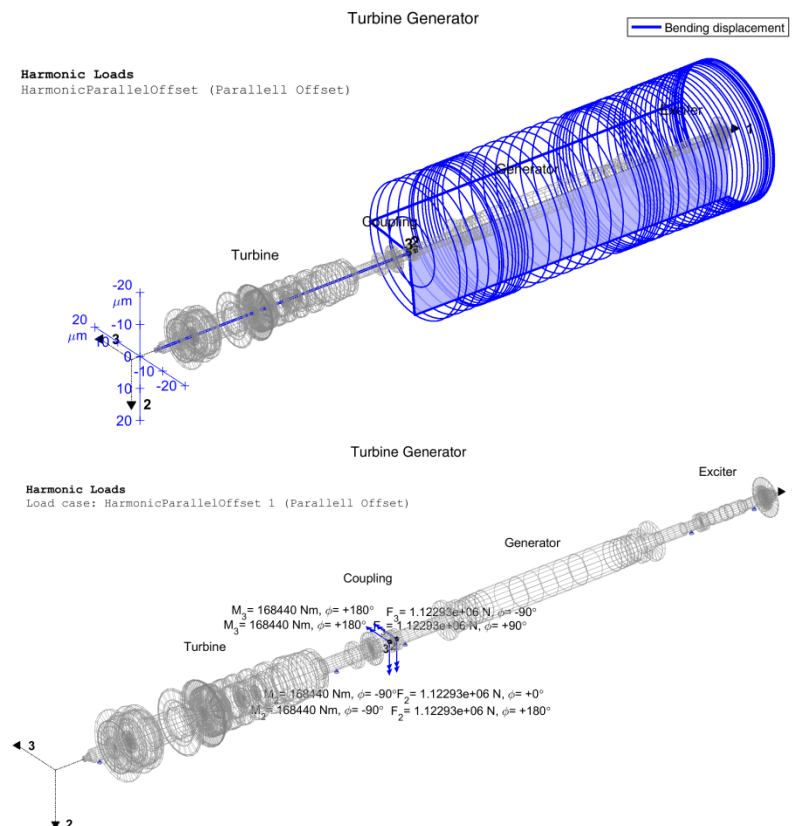


Fig. 1.8: Plots for the visualisation of a parallel offset (shape and forces)



- 7 -

### 1.3 New Non-Synchronous Excitations (Speed Multiples, Integer and Non-Integer Harmonics)

Integer and non-integer harmonic (INIH) excitations in previous versions can be defined for transient response analyses of the type  $f(n)$  and  $n(t)$  (see MADYN 2000 documentation chapter IV.5.1). In version 4.4 such excitations can also be defined for harmonic response analysis. The exciting frequency for this type of excitation is defined as a combination of speed and a frequency according to the following formula:

$$f_e = i_n n + i_f f \quad (1.5)$$

In motors driven via a frequency converter (VFD) torque excitations with frequencies of such a combination may occur, where  $i_n$  and  $i_f$  are integer numbers. However, also floating point numbers such as 0.5 can be defined as INIH loads.  $i_f = 0$  means the exciting frequency is a speed multiple.

The GUI to define an INIH excitation is shown in figure 1.9. Apart from the usual inputs of forces and moments at stations it allows defining a frequency, speeds and the factors  $i_f$  and  $i_n$ .

Fig. 1.9: GUI to define a INIH excitation

The defined forces and moments for INIH excitations may vary with the speed. They can be multiplied with a speed function  $f(n)$ . The speed function is defined in a separate window (see figure 1.10), which is invoked by the button “add Function”. Once a function is added the text of the button turns blue and shows the number of added functions. The number of factors in the function GUI (figure 1.10) must agree with the number of speeds in the INIH load GUI (figure 1.9). The plot of the function of our example is shown in figure 1.11.



- 8 -

HEF - HarmonicFunction (from: Harmonic INIH 4 24n Integer Harmonic)

Created: 05-Jan-2017 12:26:26 Modified: 05-Jan-2017 12:45:54

HarmonicFunction Title: Amplitudes 24n

---

$F_{nf_i}$  [---]

0.0399857 0.0399857 0.0747975 0.0956058 0.0922315 0.069736

$\Phi_{nf_i}$  [°]

0 0 0 0 0 0

Cancel Delete Plot << >> Add Exit

Fig. 1.10: Window to define the function  $f(n)$  for the INIH excitation

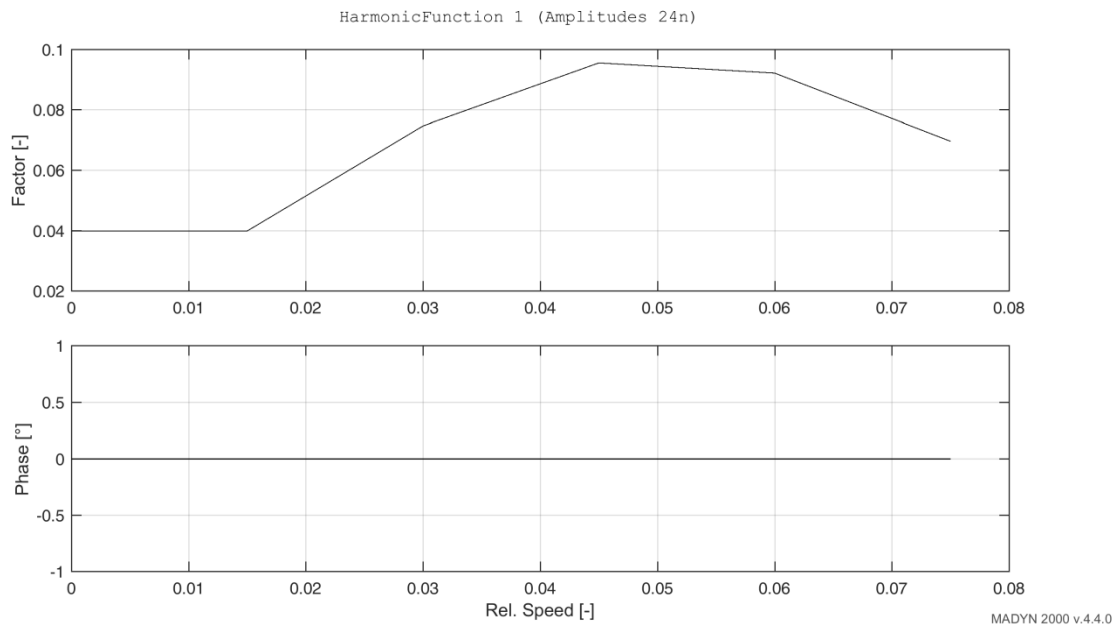


Fig. 1.11: Plot of the function in figure 1.10

The GUI to start an analysis with INIH excitation is shown in figure 1.12. A check box activates this analysis type. The usual controls and edit fields to define a speed range, speed dependent bearing properties, additional damping and to select results are available similar to a synchronous response analysis. In contrast to the synchronous analysis not a speed step, but an excitation frequency step and additionally a cut off frequency is defined. The latter has the effect of not further refining the step, if the frequency is below this limit. This is necessary in case a relative step is defined, because exciting frequencies can be zero for INIH excitation thus causing zero frequency step.

In a lateral analysis the correct frequency dependent bearing characteristics (magnetic bearings, tilting pad fluid film bearings with frequency dependent characteristics) and speed dependent characteristics (fluid film bearings, rolling element bearings) are automatically considered.



- 9 -

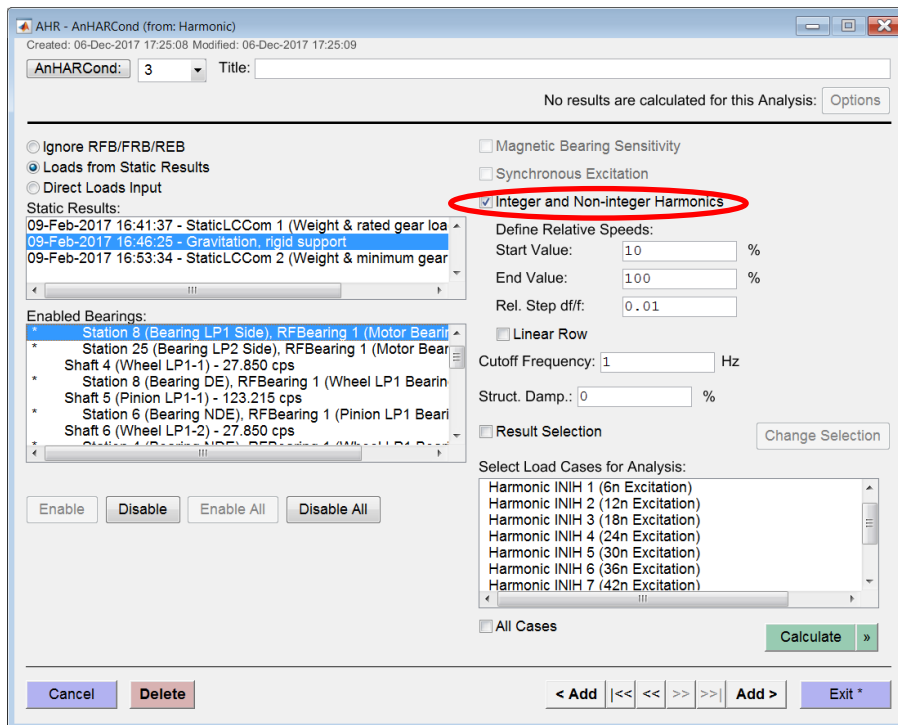


Fig. 1.12: GUI to define analysis parameter for the response analysis to INIH excitation

A special resonance plot as shown in figure 1.13 is available as result plot. In addition to the amplitude and phase angle versus speed, the excitation frequency is shown as a function of speed.

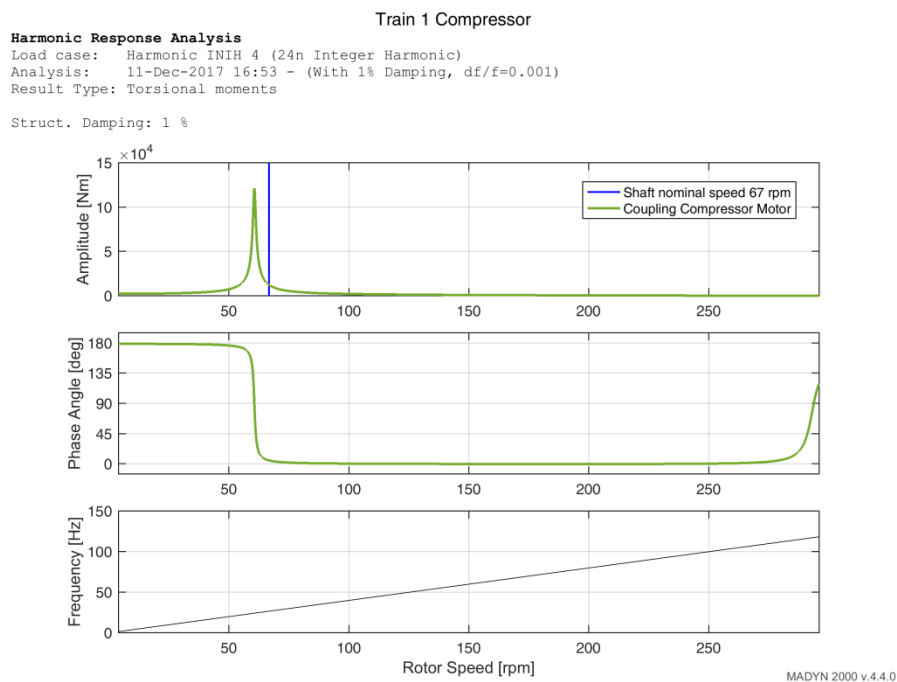


Fig. 1.13: Resonance plot for an INIH excitation (response torque in a coupling shaft to 24xn)



- 10 -

## 1.4 Load Case Combinations

In version 4.4 harmonic loads for synchronous excitation can be combined. This was not possible in previous versions. Moreover the newly implemented INIH excitations can be combined.

**Combinations of synchronous excitations:** All synchronous excitations as described above can be combined. In case there are several "bent shaft" or "offset" loads the load combination is visualised as in the above described shape plots. The boundary condition for this plot, however, is different. The shaft is free. The force plot is similar for these loads. In case a combination also has unbalances, they are shown together with the forces. An example is shown in figure 1.15. The force plot in the figure is shown as list, in contrast to the plots in chapter 1.2. This is a general option. The list in version 4.4 is more compact than in previous versions.

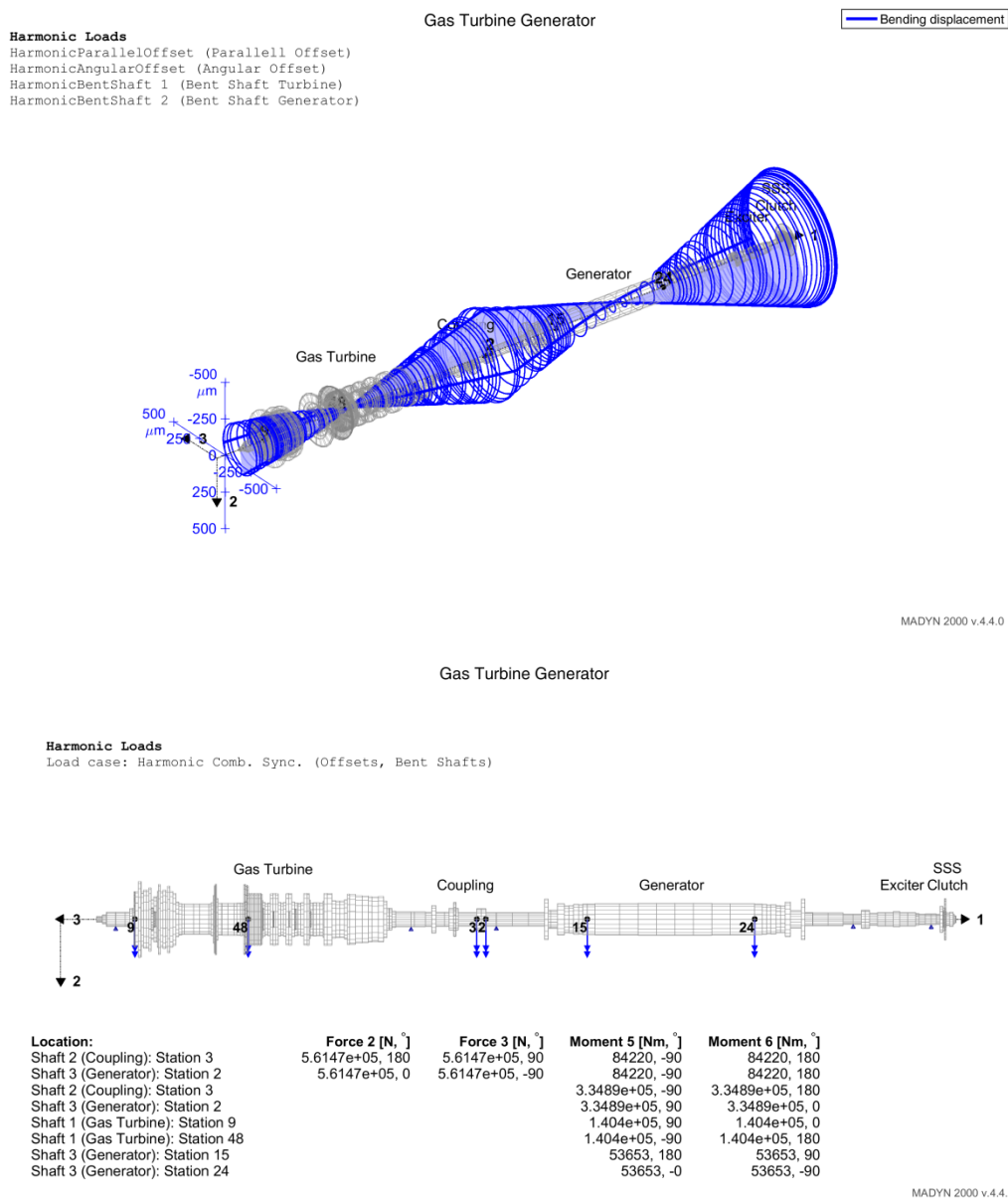


Fig. 1.16: Load plot (shape and forces) of a combination of bent shaft and offsets



- 11 -

**Combinations of integer and non-integer harmonic excitations:** Several INIH harmonic excitations can be combined to one load case. Results are then superimposed and additional plots for their presentation are available.

In figure 1.17 a spectrogram is shown for a coupling torque response to excitations from 6xn to 48xn in steps of 6n. A resonance at about 24Hz can be clearly seen for the different excitation orders. In figure 1.18 a plot of the maximum torque as a function of speed of the same response is shown.

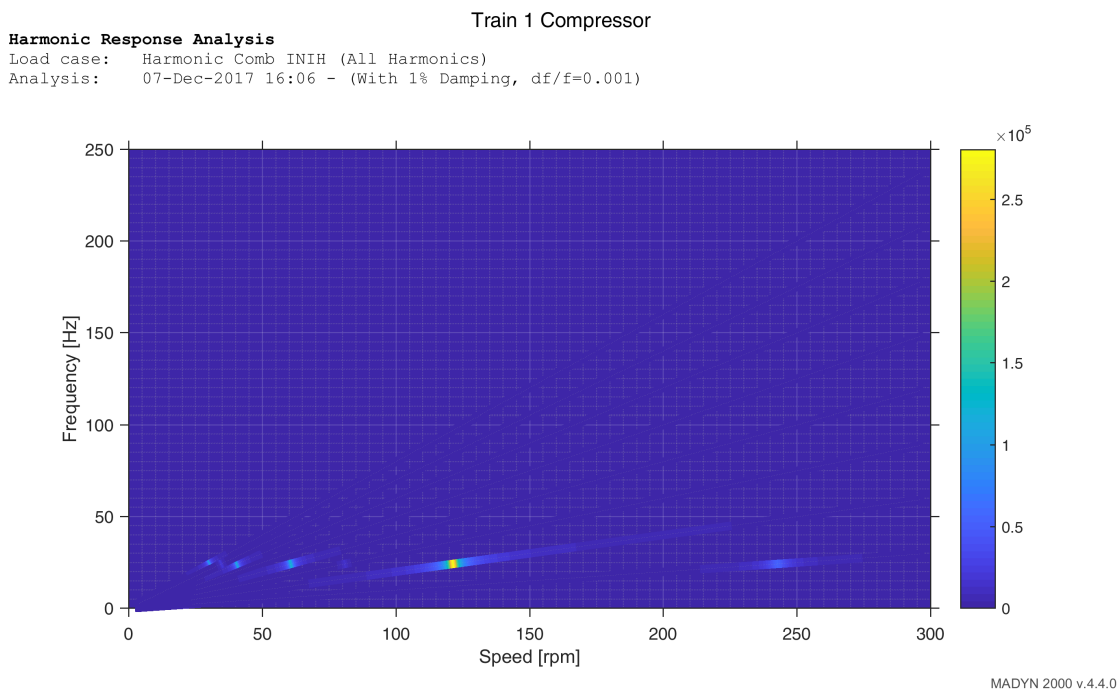


Fig. 1.17: Spectrogram, combination of INIH excitations, 6xn, 12xn, 18xn, ... 48xn

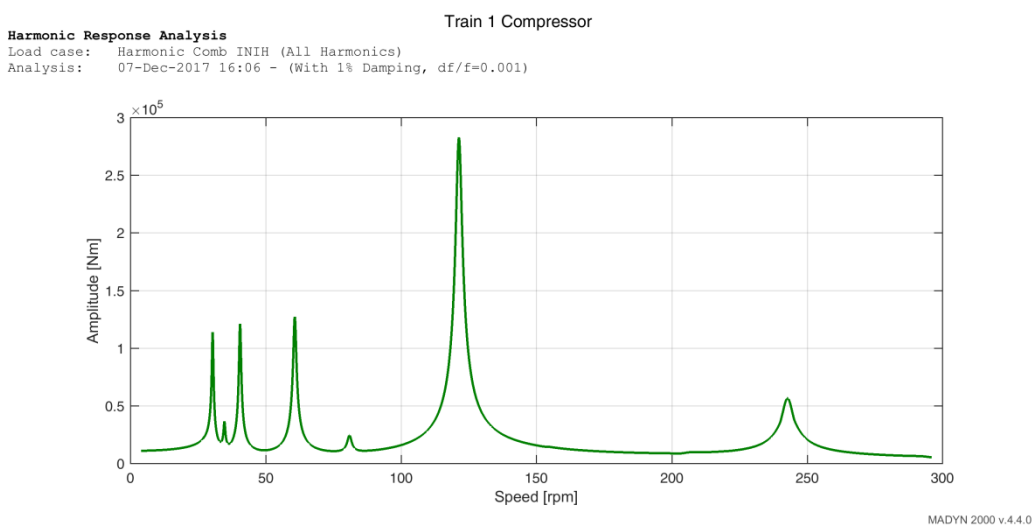


Fig. 1.18: Plot of maxima as a function of speed, same response as in figure 1.17



## 1.5 Balancing

Balancing is a new special type of analysis, which allows identifying the following synchronous harmonic loads from a measurement (also see chapter 1.1 and 1.2 of this document):

- Unbalance
- Bent shaft
- Angular offset
- Parallel offset

The GUI for balancing can be seen in figure 1.19. It has all the controls of a normal unbalance response analysis to define bearing loads, a speed range, structural damping, activation of DBS, FDCs, if such objects are in the system, and to select a load case. Additionally speeds for balancing and a final assessment can be defined.

The speeds for balancing are those speeds, which are picked from the measurement, to identified synchronous loads. These speeds of course must be within the speed range of the measurement. The measurement is defined in a separate GUI, which can be seen in figure 1.20.

The relative speeds for final assessment are used to calculate the response to the identified loads at the measurement locations. The goal is to receive a good agreement with the measurements. The response can be plotted in the same way as the response to any synchronous load.

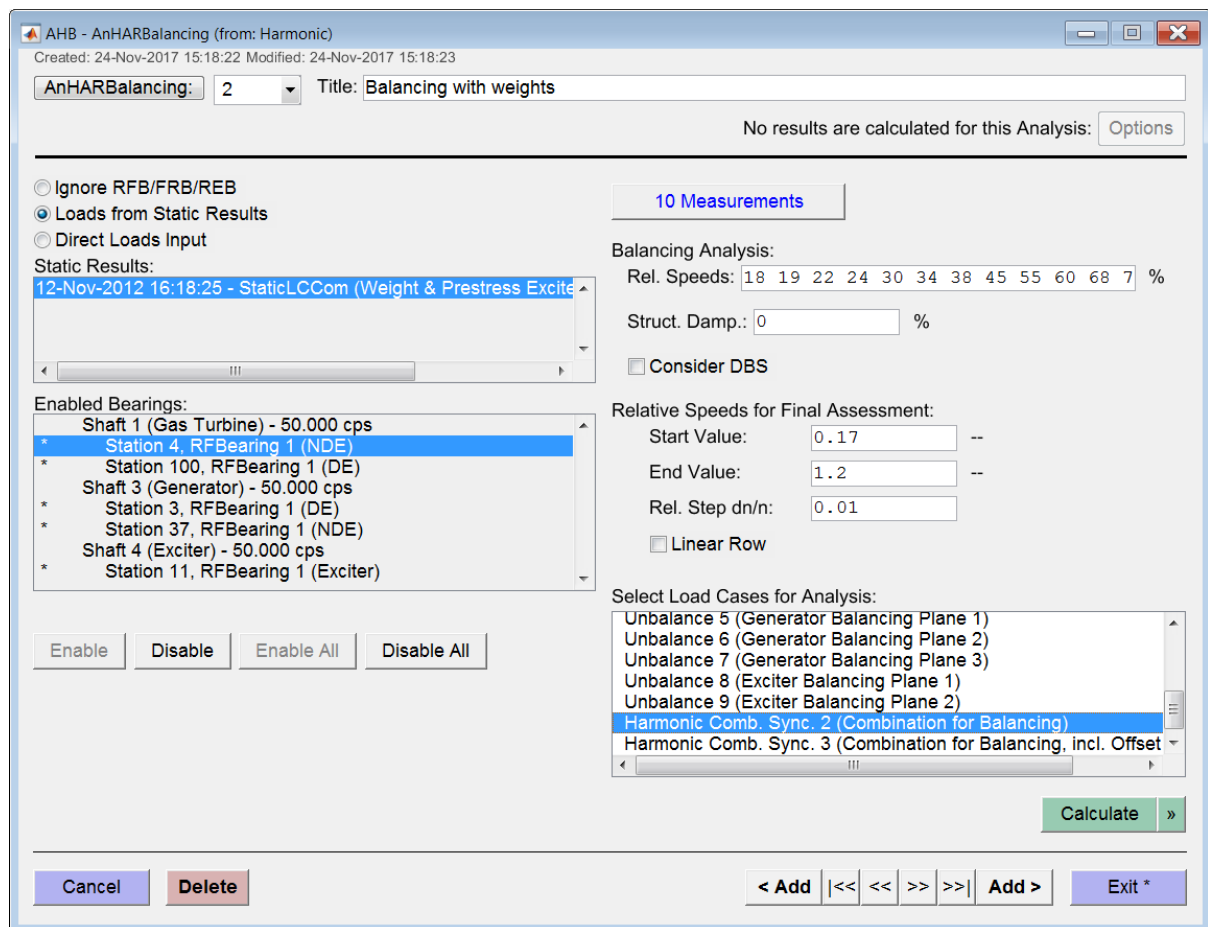


Fig. 1.19: GUI for balancing



- 13 -

The load case for balancing is typically a load case combination with several synchronous loads. For each of the loads complex factors are identified, by which they have to be multiplied to get a best match with the measurement at the balancing speeds. The complex factors can be printed as magnitude and phase angle. Offsets or bent shafts can be identified as well, if they are part of a load case combination. For pure balancing purposes a load case should only contain unbalances, for example unit unbalances in the balancing planes or sets of modal unbalances. The balancing weights have to be applied in the opposite direction of the identified unbalances.

The measurement GUI in figure 1.20 allows defining the measurement location in the system and measurement direction. Absolute shaft vibrations, relative shaft vibrations and support vibrations can be defined. Moreover a weight factor can be defined, by which the measurement is multiplied in the identification process. Measurements currently can be copied and pasted into the edit fields from a table. A button allows plotting them.

Fig. 1.20: GUI to define measurements for balancing

The identification of the factors is based on influence numbers for each of the loads in the load case combination and a least square fit to the measurements. The influence numbers can be seen in the print of the analysis results. The sum of standard deviations to the measurement at the balancing speeds is shown in the description of the results in the system GUI.

The whole balancing process is demonstrated in the following by means of load plots, measurements and resonance curve plots for the final assessment and some prints:

- Measurement at the turbine drive end, relative vibration direction as in figure 1.20: Figure 1.21
- Plot of resonance curve, response to identified loads: Figure 1.22
- Load case combination with "unit balancing weights" in the balancing planes: Figure 1.23
- Print of complex factors for balancing loads: Figure 1.24
- Mean square deviation of the response to identified loads: Figure 1.25



- 14 -

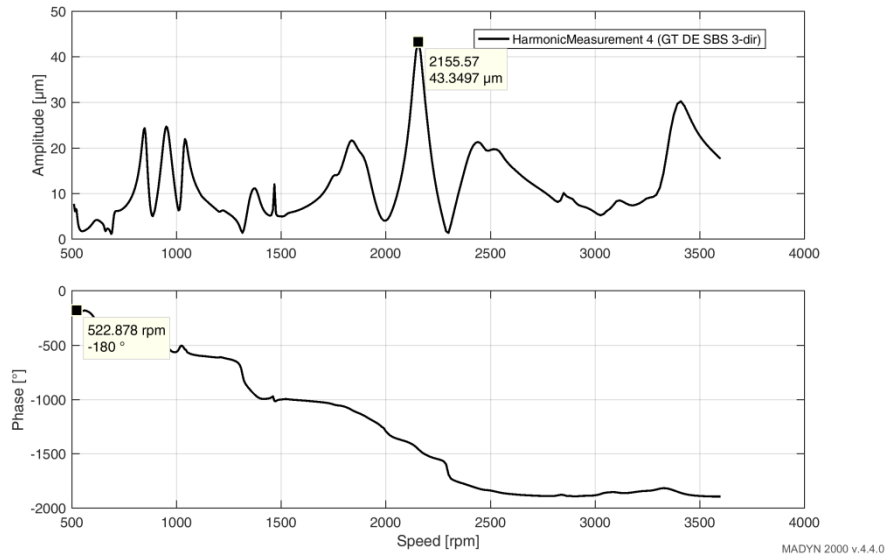


Fig. 1.21: Measurement at the turbine drive end, relative vibration direction as in figure 1.20

#### Gas Turbine Generator

**Harmonic Response Analysis** (SBS substituted by DBS)

Load case: Harmonic Comb. Sync. 2 (Combination for Balancing)

Analysis: 03-Nov-2017 16:38 - Balancing, (Balancing with weights) 14 rel.speeds (0.18...1), bearir

Result Type: Bending displacement (SBS Rel.Vibration)

Struct. Damping: 0 %

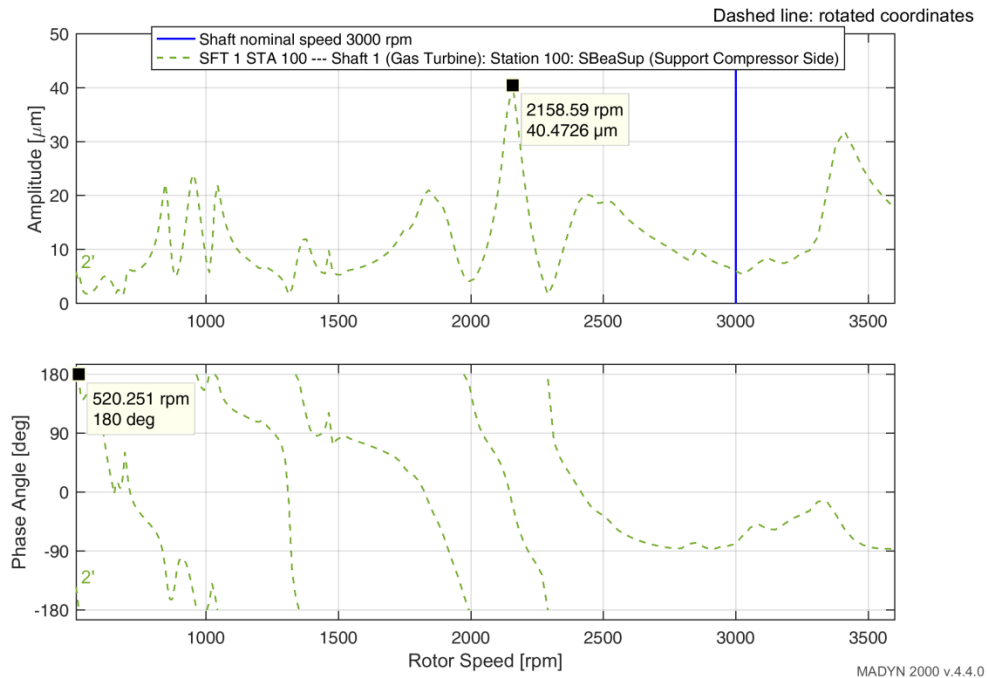


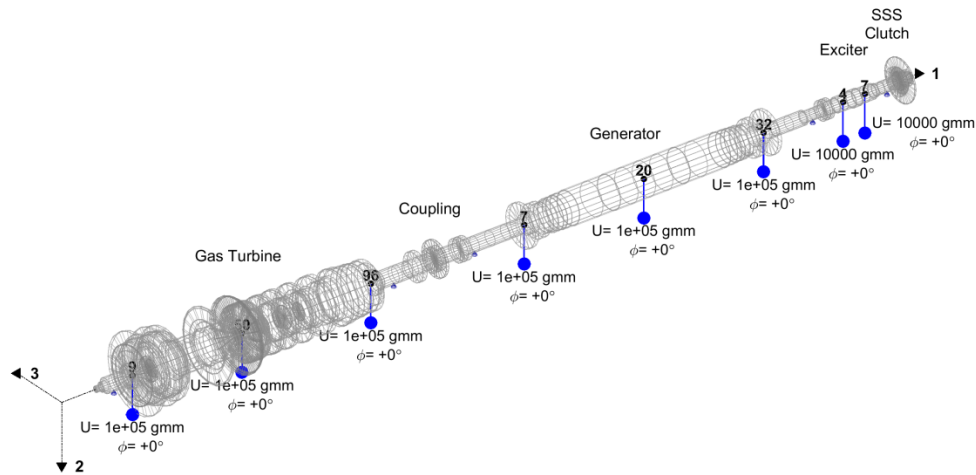
Fig. 1.22: Resonance curve of the response to identified load

The agreement of the resonance curves of the original measurement (figure 1.21) and the response to the identified unbalance (figure 1.22) is very good. The mean square deviation is  $2\mu\text{m}$ . It is shown in the system explorer in the result description (see figure 1.25).



- 15 -

**Gas Turbine Generator**  
 Load case: Harmonic Comb. Sync. 2 (Combination for Balancing)  
 Unbalance Reference Speed: 3000.00 rpm



MADYN 2000 v.4.4.0

Fig. 1.23: Unit balancing weights for balancing

### Analysis Parameters:

Dynamic Bearing Support (DBS) is considered instead of SBS.

| Load Case:                                | Factor, % | Phase, deg |
|-------------------------------------------|-----------|------------|
| Unbalance 2 (Turbine Balancing Plane 1)   | 1053.53   | -0.3       |
| Unbalance 3 (Turbine Balancing Plane 2)   | 752.30    | +25.9      |
| Unbalance 4 (Turbine Balancing Plane 3)   | 463.94    | +38.5      |
| Unbalance 5 (Generator Balancing Plane 1) | 497.76    | +78.6      |
| Unbalance 6 (Generator Balancing Plane 2) | 1792.05   | +62.7      |
| Unbalance 7 (Generator Balancing Plane 3) | 325.67    | +81.1      |
| Unbalance 8 (Exciter Balancing Plane 1)   | 2870.29   | -1.1       |
| Unbalance 9 (Exciter Balancing Plane 2)   | 1969.98   | -175.7     |

Fig. 1.24: Complex factors for unit balancing weights

**System**  
 Static  
 Loads  
 An. Param.  
 Results  
 Eigenvalue  
 An. Param.  
 Results  
 Harmonic  
 Loads  
 An. Param.  
 Results =====>>  
 Transient

**1. Result:** 02-Nov-2017 15:34 - 393 rel.speeds (0.17...1.2), bearing loads from SAN, sync., DBS, Harmonic Comb. Sync. 1 (Arbitrary Unbalance, Offsets, Bent Shafts)

**2. Result:** 03-Nov-2017 16:38 - Balancing, (Balancing with weights) 14 rel.speeds (0.18...1), bearing loads from SAN, D Harmonic Comb. Sync. 2 (Combination for Balancing) **Fit Std.Error: 2.0 µm**

**3. Result:** 05-Nov-2017 13:38 - Balancing, (Balancing with weights, factor exciter vibration 0) 14 rel.speeds (0.18...1), b Harmonic Comb. Sync. 2 (Combination for Balancing) = Fit Std.Error: 3.8 µm

Fig. 1.25: Mean square deviation shown in system explorer



## 2. Active Systems (Magnetic Bearings)

### 2.1 Import of State Space Controllers

Controllers can be designed within MADYN 2000 by combining controller building blocks and optimizing their parameters. This method is basically a SISO (single input output) approach with the additional capability to implement special types of couplings between bearings and axes. It is practically proven.

However, other methods exist. Controllers can also be designed with the MATLAB robust control toolbox for example. For this purpose the speed dependent rotor system can be exported (see next chapter 2.2).

An externally designed controller can be a state space controller, which includes couplings between axes and bearings. In version 4.4 such a controller can be imported on system level with the help of a button in the system GUI (see figure 2.1).

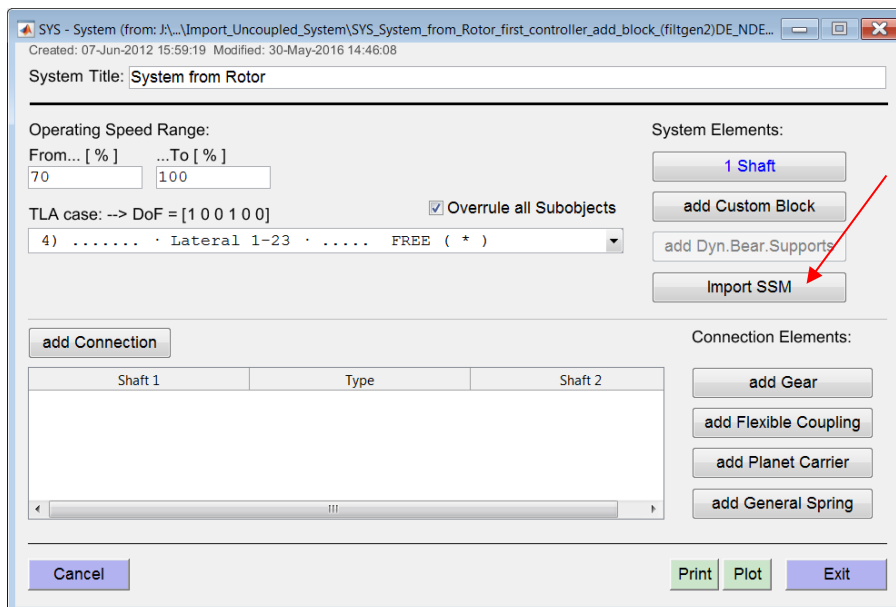


Fig. 2.1: System GUI with new button to import state space controller system

The state space matrices of the controller are part of a MATLAB structure "ImportSSM" with the fields "Matrices" and "Description":

```
ImportSSM =  
  
    Matrices: [1x1 struct]  
    Description: [1x4 struct]
```

The field "Matrices" contains the state space matrices A,B,C,D. "Description" is a structure array describing the inputs and outputs of the state space controller. Inputs are the sensor signals and outputs are the forces applied to the rotor system. Each element of the array describes a location and direction. The dimension 4 as in the example here applies to a typical system with one shaft and two radial magnetic bearings.



- 17 -

The state space matrices are stored in different fields with the names of the matrix:

```
ImportSSM.Matrices  
  
A: [60x60 double]  
B: [60x4 double]  
C: [4x60 double]  
D: [4x4 double]
```

The sensor and actuator locations and directions (inputs and outputs) in the field “Description” are stored in two structures:

```
ImportSSM.Description(1)  
  
Sensor: [1x1 struct]  
Actuator: [1x1 struct]  
  
ImportSSM.Description(1).Sensor  
  
direction: 2  
address: 'System.Shaft("Rotor").Station(9) '  
  
ImportSSM.Description(1).Actuator  
  
direction: 2  
address: 'System.Shaft("Rotor").Station(10) '
```

Shafts and stations are either described by their denotation or by their number. In case a state space controller is imported to a system without a rotor with the requested number/denotation or the rotor does not have the necessary station numbers/denotations an error message appears.

Once a state space controller has been imported the active system GUI of a certain type (normally a radial magnetic bearing) can be opened from the shaft GUI to define a magnetic pull and to plot the transfer functions. Note, that the plot of a bearing contains all transfer functions involving the sensor and actuator of the current bearing, i.e. also the transfer functions of couplings to other bearings and directions:

Current bearing / direction → current bearing / other directions and other bearings / directions.

For a system with one rotor with two bearings and a fully coupled state space controller 12 transfer functions are plotted for each bearing. In case directions are not coupled only 6 transfer functions are plotted. Note, that only non-zero transfer functions are plotted.

## 2.2 Export of Modally Reduced Rotor State Space Systems

Bi-modally reduced state space matrices of a system can be exported to a MATLAB mat-file in version 4.4. The purpose for such an export can be designing a controller outside MADYN 2000 in MATLAB or using the system in a SIMULINK simulation. For the export the system must contain active systems with defined sensor / actuator locations and directions. Controllers do not have to be defined. The displacements (or velocities in case of velocity measurement) at sensor locations and directions are the outputs of the system and the forces at actuator locations / directions the inputs to the system.

The matrices are exported from the print window of eigenvalue or Campbell diagram results with the help of “Export” button (see figure 2.2). The export is only possible in case the analysis has been carried out including left eigenvectors and with deactivated active systems. For the modal reduction all calculated natural modes in the result are considered. State space matrices for several speeds can be exported. The speeds can be selected in the print window.



- 18 -

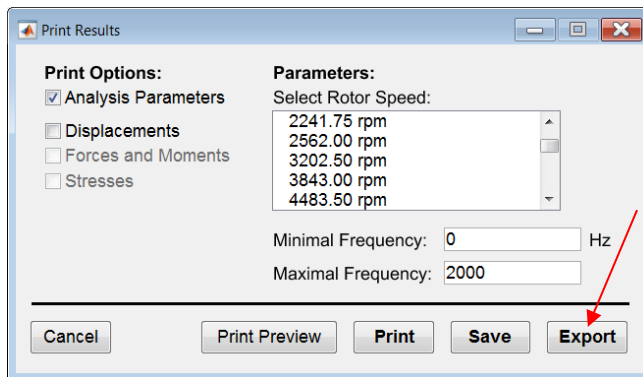


Fig. 2.2: System GUI with new button to export state space rotor systems

The exported file is a structure "SystemSSM" with the fields "Matrices" and "Description."

```
SystemSSM =  
  
    Matrices: [1x17 struct]  
    Description: [1x4 struct]
```

The field "Matrices" is a structure array with the speed dependent state space matrices. The dimension corresponds to the number of speeds. The present example has 17 speeds. "Description" is a structure array describing the outputs (sensor signals) and inputs (forces at the actuators) of the system. Each element of the array describes a location and direction. The dimension 4 as in the example here applies to a typical system with one shaft and two radial magnetic bearings.

The state space matrices for each speed are stored in different fields with the names of the matrix as shown below. The A-matrix is a diagonal with the eigenvalues. The D-matrix is always zero for a rotor system and is not stored. All matrices are complex. The A-matrix also contains the conjugate complex eigenvalues and the B and C matrices are calculated with consideration of the conjugate complex eigenvectors.

```
SystemSSM.Matrices  
  
1x17 struct array with fields:  
  
    Adiaq  
    B  
    C  
    Speed
```

The sensor and actuator locations and directions (actuator is input and sensor output, i.e. vice versa to the input and output of the space controller) in the field "Description" are stored in two structures in a similar way as described in the previous chapter for the import of a state space controller:

```
SystemSSM.Description(1).Sensor  
  
    direction: 2  
    address: 'System.Shaft("Motor Compressor SBS").Station(8)'  
  
SystemSSM.Description(1).Actuator  
  
    direction: 2  
    address: 'System.Shaft("Motor Compressor SBS").Station(10)'
```



## 2.3 Export of Controllers

Controllers designed in MADYN 2000 can now be directly exported to a MATLAB mat-file by an export button in the controller GUI (see figure 2.3). The file contains a MATLAB controller object with the transfer function in polynomial form named “syscg” similar to the block “contgen” for import of a single input output controller object.

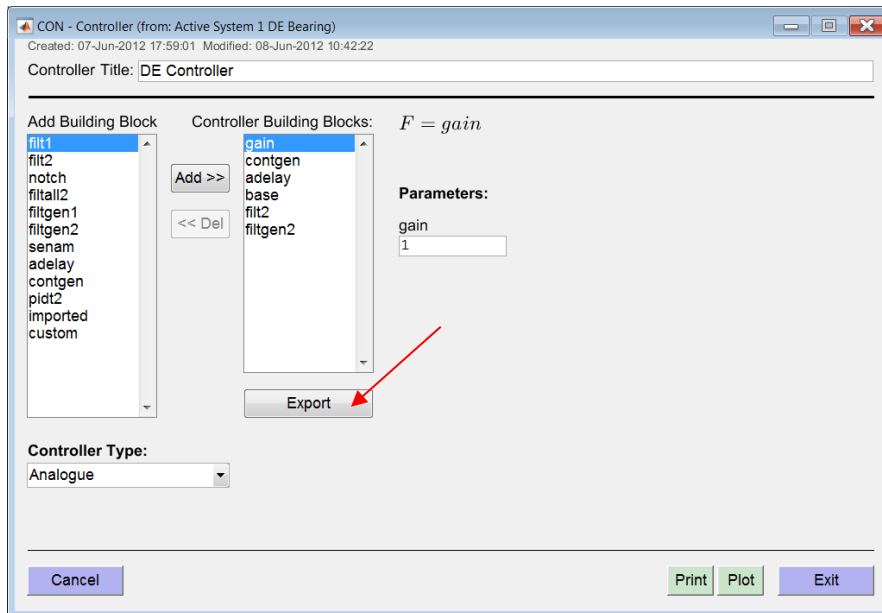


Fig. 2.3: System GUI with new button to export a controller to a MATLAB mat-file

## 3. Fluid Film Bearings

### 3.1 Bearing Data in Analyses

For “user defined” bearings the stiffness and damping coefficients describing the characteristics in linear rotordynamic analyses until now had to be pre-calculated. Later in an analysis the stored results are interpolated for the actual load for example from a static analysis.

In version 4.4 the pre-calculation is no longer necessary. The analysis is carried out directly on demand in case any load in the actual rotordynamic analysis does not exist or cannot be interpolated. In case of complex loads as they can occur in gears this facilitates the procedure of a harmonic response analysis or a Campbell diagram considerably.

In some analyses as for example in some harmonic response analyses very fine speed steps may be necessary. Therefore in all analyses the bearing analysis on demand is not carried out for every step, but for automatically created reasonable steps. The loads of an “on demand analysis” appear as additional load variant in the RFB object. The load and results can be viewed there.

The analysis on demand works especially well in case of analysis type constant and variable adiabatic. In case of DIN it also works, however, because of the additional internal DIN iteration for the actual mean temperature it can fail in extreme cases.

The static RFB results of an automatically created RFB load variant from the analysis in figure 3.1 are shown in figure 3.2. The corresponding coefficients are shown in figure 3.3. It can be seen, that the load changes its direction and magnitude with speed, as it happens in gears. The harmonic response analysis with the relative speed step of 3% yields 86 speeds. The automatically created load variant has 17 speeds.



- 20 -

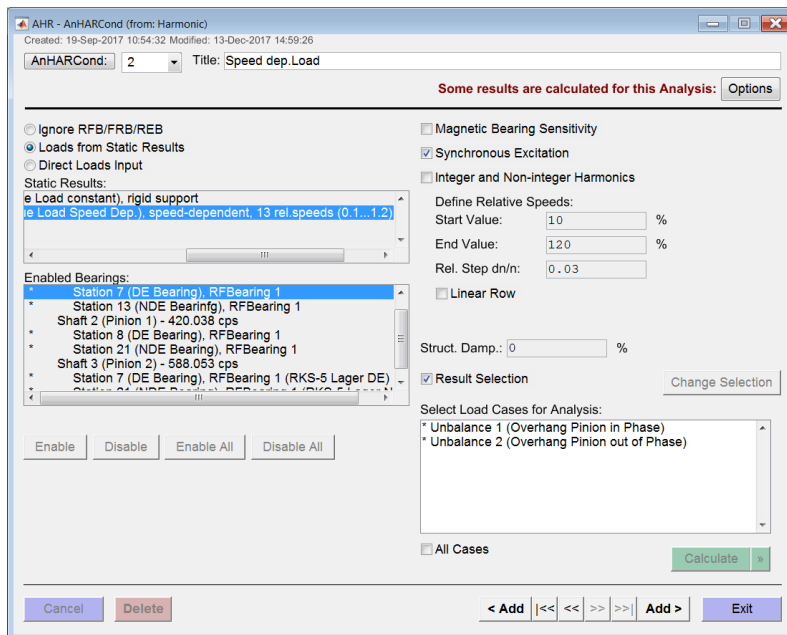


Fig. 3.1: Harmonic response analysis GUI with speed dependent static load

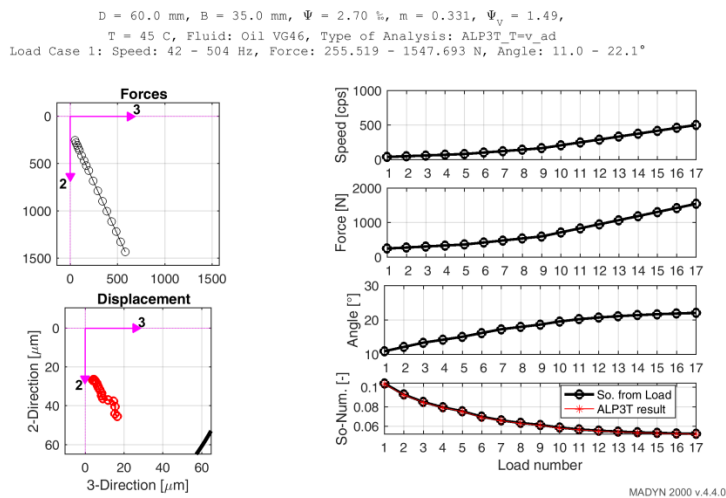


Fig. 3.2: Static RFB result of automatically created load variant from the analysis in figure 3.1

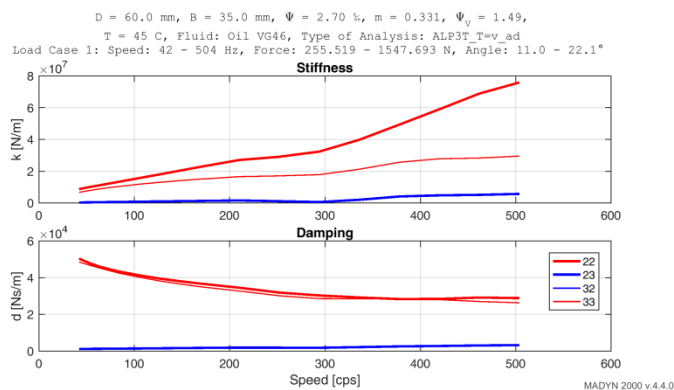


Fig. 3.3: Bearing coefficients of automatically created load variant from the analysis in figure 3.1



### 3.2 Field Plots of Results

The analysis to find the equilibrium position to a bearing load yields results such as the pressure and temperature distribution in the bearing, which are stored in fields and can be plotted now. The following field plots are available:

- Oil Film Thickness
- Pressure
- Oil Fraction (1 means 100% oil, 0 means full cavitation)
- Deformations (thermal, elastic, total)
- Oil Velocities (mean radial and mean circumferential)
- Temperature (shaft surface, maximum in the oil across clearance, mean radial in the oil, pad surface)
- Turbulence related plots (axial and circumferential turbulence correction factors)

The field plots are called as follows from the RFB GUI: The button “List Results” opens the window shown in figure 3.4. The button “Plot Detailed Results” is activated, if one or several results in the list are selected (highlighted in blue). It opens the window in figure 3.5 to select the desired field plots by check boxes. In figure 3.6 a plot with the probably most important results (oil film thickness, pressure, pad surface temperature) is shown.

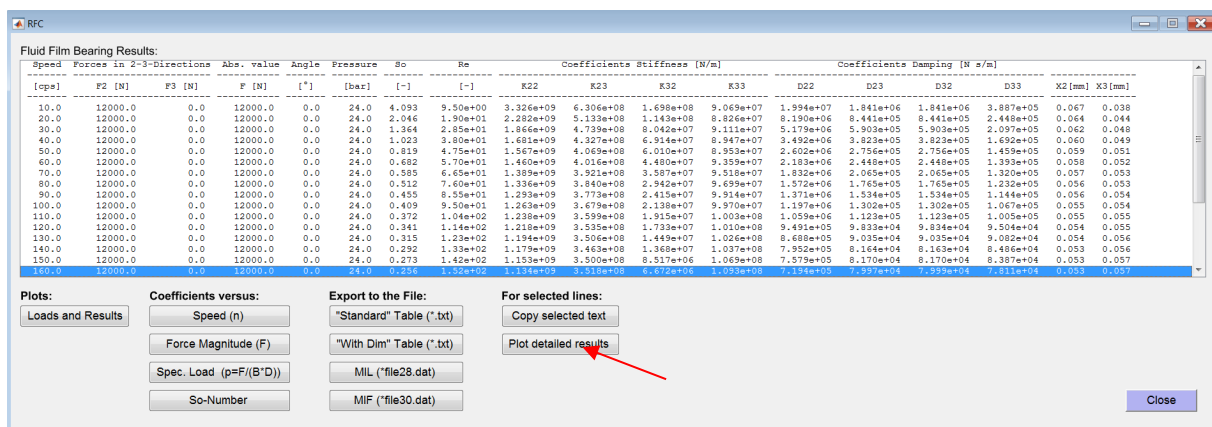


Fig. 3.4: GUI to call field plots



- 22 -

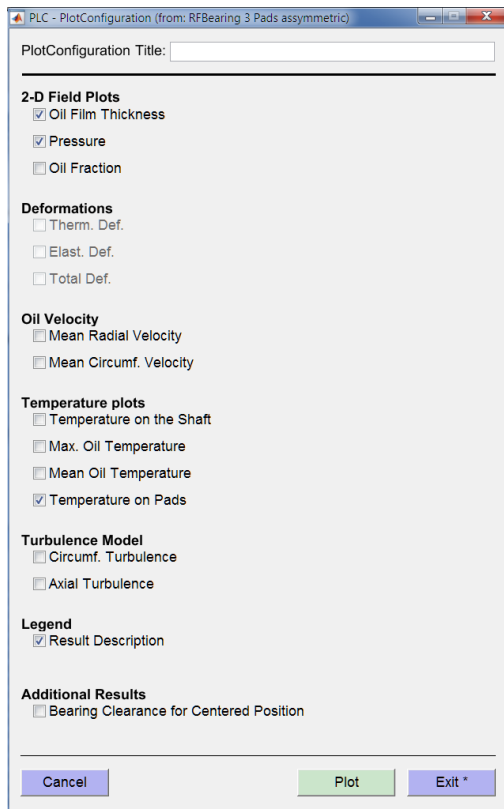
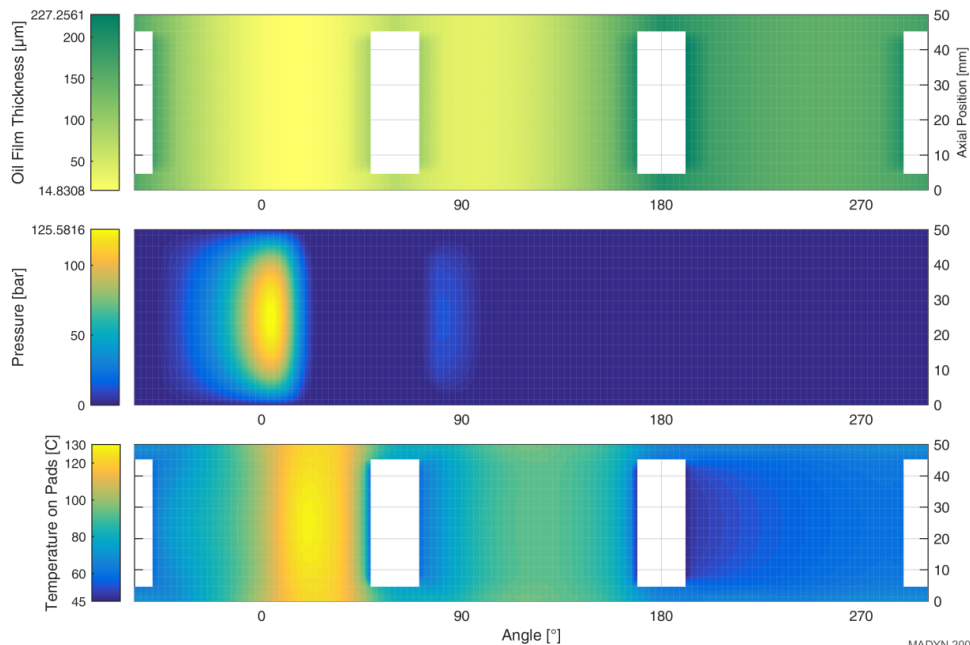


Fig. 3.5: Window to select results for the field plot

Load Case: Speed: 200 Hz, Force: 12000.000 N, Angle: 0.0°  
 3 Pads v\_ad Pockets high load  
 $D = 100.0$  mm,  $B = 50.0$  mm,  $\Psi = 1.50$  %,  $m = 0.667$ ,  $\Psi_v = 3.00$ ,  
 $T = 45$  C, Fluid: Oil VG32 Shell, Type of Analysis: ALP3T\_T=v\_ad



MADYN 2000 v.4.4.0

Fig. 3.6: Field plots



### 3.3 Axial Thermo-Elastic Pad Deformation for Tilting Pad Bearings

Thermo-elastic pad deformation of tilting pad bearings now also considers the deformation in axial direction, whereas previously only the deformation in circumferential direction was taken into account.

In figure 3.7 the geometry of a bearing is shown, which has been analysed and measured in a research project of FVV (Forschungsvereinigung Verbrennungskraftmaschinen). The results are documented in a thesis<sup>1</sup>. The MADYN 2000 results are shown in figure 3.8 (oil film thickness, pressure distribution and pad surface temperature) and figure 3.9 (deformations). A comparison of the results to those in the thesis yields good agreement as summarised in table 3.1.

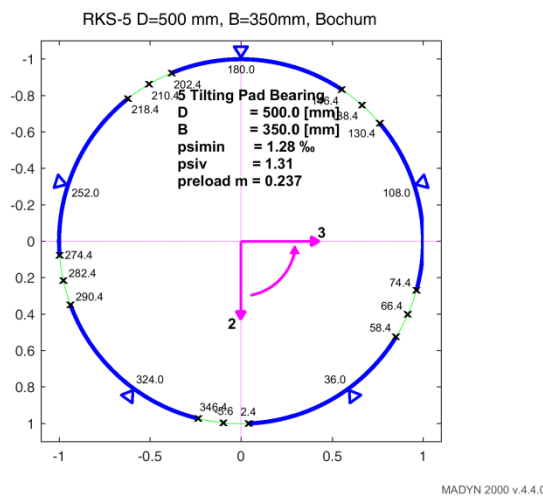


Fig. 3.7: Geometry of the bearing tested in Bochum, Germany

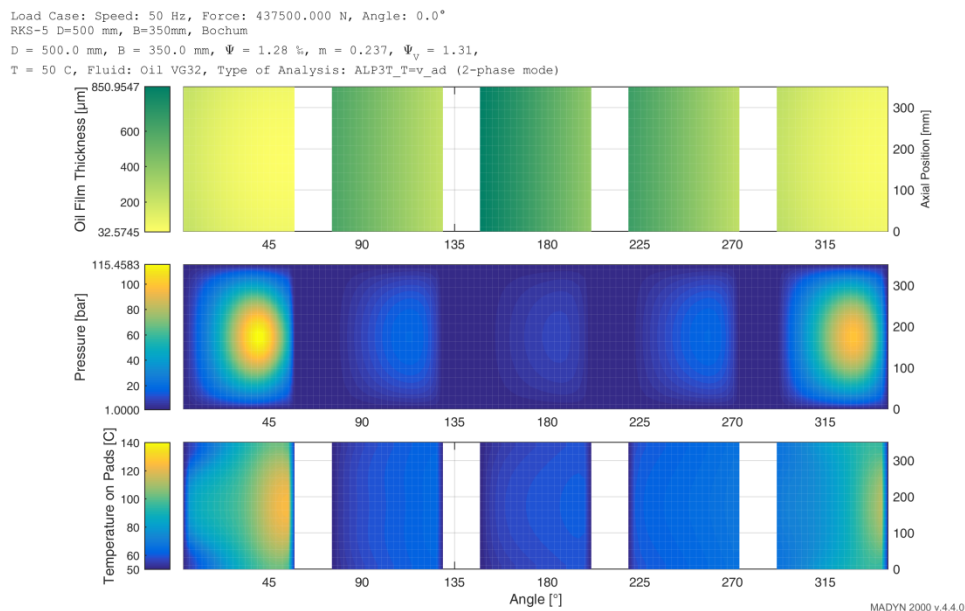


Fig. 3.8: Field plots of MADYN 2000 results for oil film thickness, pressure distribution and pad surface temperature

<sup>1</sup> Thomas Hagemann, Ölzuführeinfluss bei schnell laufenden, hoch belasteten Radialgleitlagern unter Berücksichtigung des Lagerdeformationsverhaltens, Fortschrittsberichte des Instituts für Tribologie und Energiewandlungsmaschinen.



- 24 -

Load Case: Speed: 50 Hz, Force: 437500.000 N, Angle: 0.0°  
 RKS-5 D=500 mm, B=350mm, Bochum  
 D = 500.0 mm, B = 350.0 mm,  $\Psi = 1.28\%$ ,  $m = 0.237$ ,  $\Psi_v = 1.31$ ,  
 T = 50 C, Fluid: Oil VG32, Type of Analysis: ALP3T\_T=v\_ad (2-phase mode)

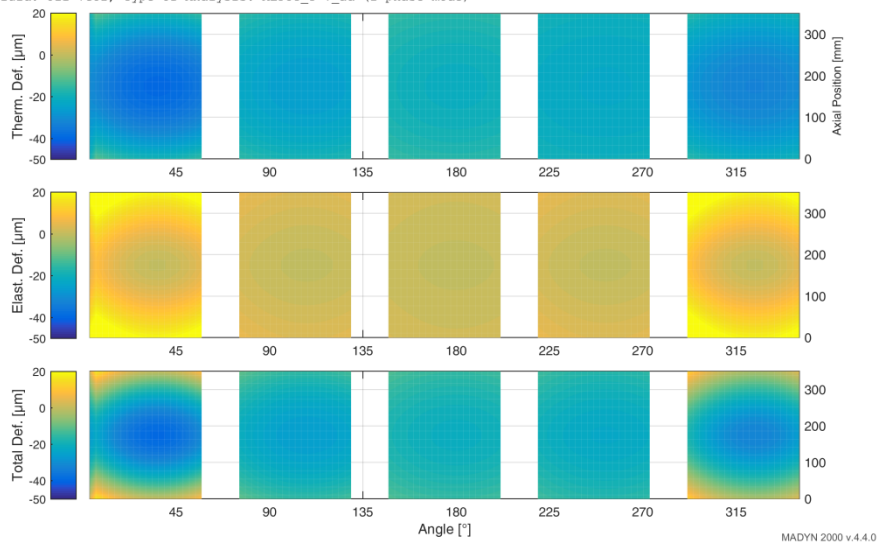


Fig. 3.9: Field plots of MADYN 2000 results for deformations

Table 3.1: Comparison of MADYN 2000 results to those in the thesis of Hagemann

| Result                                         | MADYN 2000 | Hagemann                          |
|------------------------------------------------|------------|-----------------------------------|
| Min. oil film thickness in $\mu\text{m}$       | 33         | 30 calculated (FE), 20 measured   |
| Max pressure in bar                            | 115        | 120 calculated (FE), 117 measured |
| Max. pad/oil temperature in $^{\circ}\text{C}$ | 124 / 129  | 122 measured and calculated       |
| Mechanical radial deformation in $\mu\text{m}$ | 19         | 22                                |
| Thermal radial deformation $\mu\text{m}$       | 21         | 22                                |
| Total radial deformation $\mu\text{m}$         | 39         | 42                                |

\* Measurement position is about 5 mm below the pad sliding surface.



### 3.4 Asymmetric Pockets

Hydrostatic and hydrodynamic pockets now can be axially asymmetric. The axial position is defined in the pad GUI in the field "Pocket pos." (see figure 3.10). The resulting geometry field plot in centred position and the field plots for the minimum oil film thickness, pressure and pad surface temperature resulting from an analysis are shown in figure 3.11 and 3.12.

Fig. 3.10: Pad GUI with definition of an asymmetric hydrostatic pocket

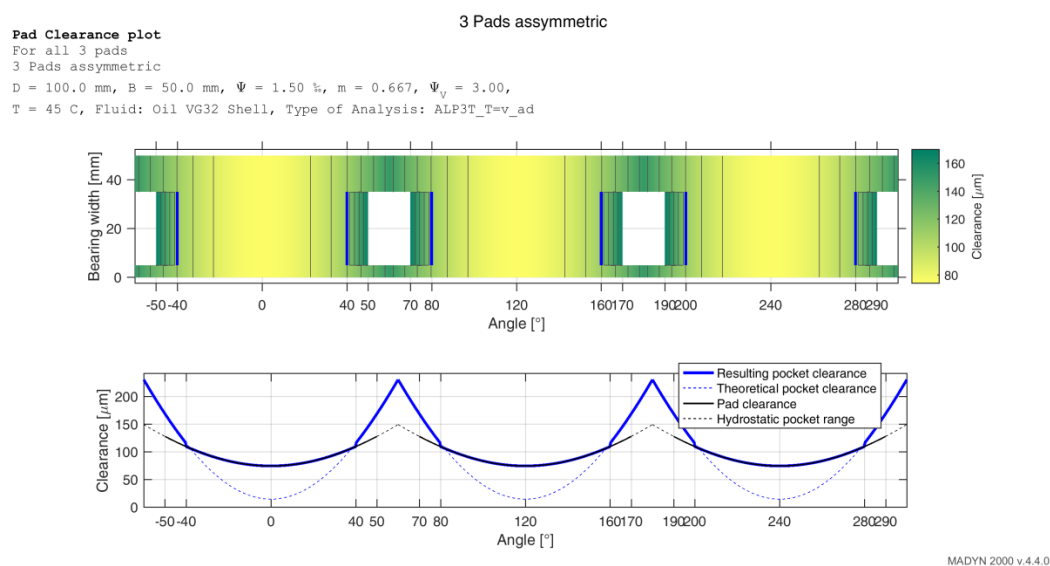


Fig. 3.11: Bearing clearance plot



- 26 -

Load Case: Speed: 200 Hz, Force: 3000.000 N, Angle: 0.0°  
 3 Pads asymmetric  
 $D = 100.0$  mm,  $B = 50.0$  mm,  $\Psi = 1.50$  %,  $m = 0.667$ ,  $\Psi_v = 3.00$ ,  
 $T = 45$  C, Fluid: Oil VG32 Shell, Type of Analysis: ALP3T\_T=v\_ad

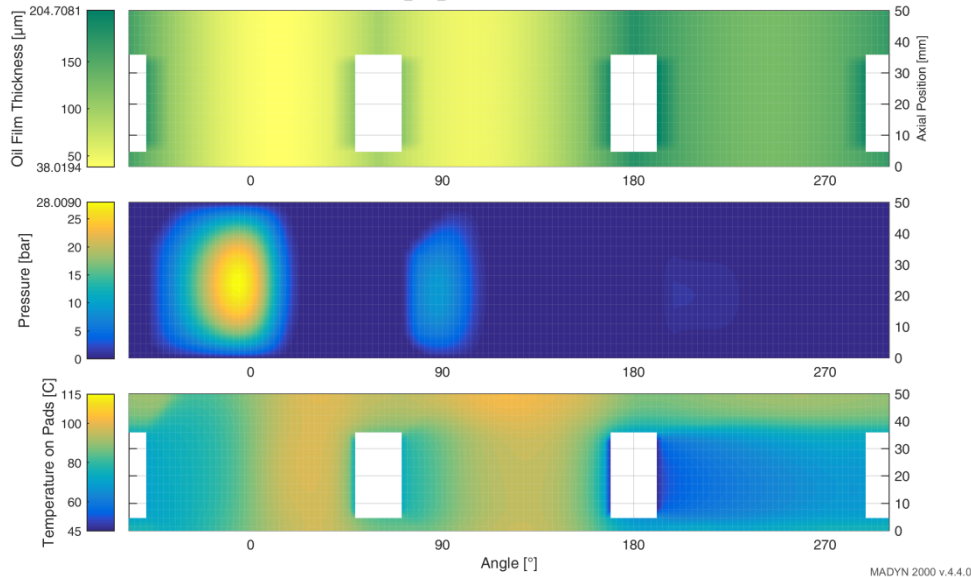


Fig. 3.12: Field plots for the minimum oil film thickness, pressure and pad surface temperature

### 3.5 Boundary Condition for Direct Lubrication of Tilting Pad Bearings

The option “Direct Lubrication” as boundary condition for the oil supply of tilting pad bearings is new (see figure 3.13). As other boundary conditions for the oil supply it is available for the analysis type “variable adiabatic” and represents the best option to simulate an oil supply through nozzles in contrast to a flooded bearing. The pad GUI then allows defining a nozzle area per pocket (see figure 3.14). The pocket in the pad GUI hereby corresponds to the pocket before the pad. Default value is 1% of the projected area of the bearing (diameter x width). The nozzle areas together with the oil supply pressure define the oil flow.

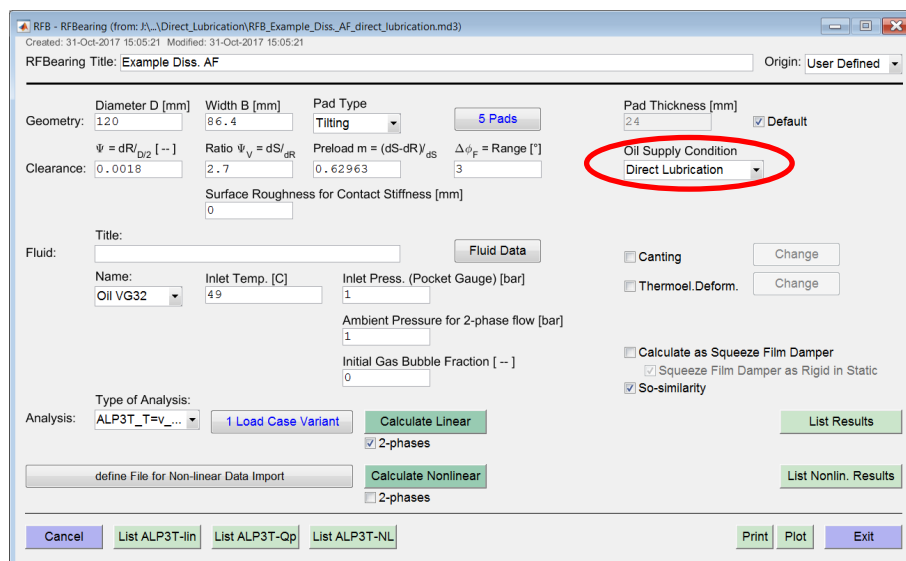


Fig. 3.13: RFG GUI with the option for direct lubrication



- 27 -

Fig. 3.14: RFB pad GUI with the filed to define the nozzle

### 3.6 Temperature Outputs in Print

The following additional temperatures are now printed in the fluid film bearing analysis results:

- |                                   |                                                                        |
|-----------------------------------|------------------------------------------------------------------------|
| Analysis type DIN:                | The maximum temperature. So far only the mean temperature was printed. |
| Analysis type variable adiabatic: | The mean temperature. So far only the maximum temperature was printed. |

### 3.7 Hydrostatic Pockets

Hydrostatic pockets are now closed automatically, if the angle between start and end of the pocket is zero. Until now hydrostatic pressure at start and end pad was assumed also for this case.



## 4. Squeeze Film Dampers

The GUI for the squeeze film damper now has a check box, which allows to specify, whether the squeeze film damper shall be considered as rigid in static analysis or not (see figure 4.1). So far the damper was always considered as rigid, because statically it cannot carry any load (load carrying capacity is only built up by vibrations). Static analysis therefore can only be carried out, if the damper is either rigid or if another support such as a squirrel cage is in parallel to the damper. For the latter case the possibility to remove the rigid option was introduced. A squirrel cage in MADYN 2000 would typically be modelled as a RSB (radial spring bearing).

RFBearing (from: Station 3)  
Created: 10-Apr-2015 15:59:40 Modified: 31-Jul-2017 19:58:26

RFBearing Title:  Origin: User Defined

Geometry: Diameter D [mm] 51 Width B [mm] 24.8 Pad Type Fixed 1 Pad

Clearance:  $\Psi = dR/d_2$  [-] 0.002 Ratio  $\Psi_v = dS/d_R$  1 Preload  $m = (dS-dR)/d_S$  0  $\Delta\phi_F = \text{Range} [^\circ]$  3

Surface Roughness for Contact Stiffness [mm] 0

Fluid: Title:  Fluid Data ☐ Canting Change

Name: Oil VG150 Mean Temp. [C] 85 Inlet Press. for 2-phase flow (Pocket Gauge) [bar] 0

Ambient Pressure for 2-phase flow [bar] 1

Initial Gas Bubble Fraction [-] 0

Type of Analysis: ALP3T-T=c... ☒ Calculate as Squeeze Film Dampers ☒ Squeeze Film Damper as Rigid in Static ☒ So-similarity

Analysis:

Fig. 4.1: GUI of the squeeze film damper with check box for static analysis behaviour

In case of a semi-floating ring bearing, where the outer film acts as a squeeze film damper and which is modelled in MADYN 2000 as an FRB (floating ring bearing) it is possible to allow a heat flow through the ring. In this case the oil temperature no longer corresponds to the inlet oil temperature of the squeeze film. Another mean temperature will arise. Therefore the mean temperature is now printed in the results as shown in figure 4.2. The output corresponds to the output of a FRB with rotating ring together with the ring speed ratio RSR, which is zero in case of a semi-floating ring.

MADYN 2000 Version 4.4.0 14-Dec-2017

**Floating Ring Bearing**

Turbine  
Created: 25-Oct-2016 16:22:52  
Modified: 25-Oct-2016 17:16:51

Floating Ring Mass: 0.760 kg

Ring Speed Ratio for Load Cases

| Rotor Speed [rpm]                                              | RSR [-] | Tmean_i [oC] | Tmean_o [oC] | Psi_i [o/oo] | Psi_o [o/oo] |
|----------------------------------------------------------------|---------|--------------|--------------|--------------|--------------|
| Load Case 1: Speed: 25 - 750 Hz, Force: 703.700 N, Angle: 0.0° |         |              |              |              |              |
| 1.500e+03                                                      | 0.000   | 68.9         | 67.5         | 1.565        | 2.052        |
| 3.000e+03                                                      | 0.000   | 72.3         | 70.0         | 1.583        | 2.025        |
| 4.500e+03                                                      | 0.000   | 75.7         | 72.6         | 1.602        | 1.997        |
| 6.000e+03                                                      | 0.000   | 78.4         | 74.7         | 1.617        | 1.976        |
| 7.500e+03                                                      | 0.000   | 80.7         | 76.5         | 1.630        | 1.957        |
| 9.000e+03                                                      | 0.000   | 82.7         | 78.0         | 1.641        | 1.940        |
| 1.050e+04                                                      | 0.000   | 84.5         | 79.3         | 1.651        | 1.926        |
| 1.200e+04                                                      | 0.000   | 86.1         | 80.5         | 1.660        | 1.913        |
| 1.350e+04                                                      | 0.000   | 87.6         | 81.6         | 1.668        | 1.901        |
| 1.500e+04                                                      | 0.000   | 88.9         | 82.6         | 1.675        | 1.889        |
| 1.650e+04                                                      | 0.000   | 90.2         | 83.5         | 1.682        | 1.879        |
| 1.800e+04                                                      | 0.000   | 91.4         | 84.4         | 1.689        | 1.869        |

Fig. 4.2: Print with the temperature of inner and outer oil film for a FRB with squeeze film damper



## 5. Interfaces

### 5.1 Import of Dynamic Bearing Supports from ANSYS

In ANSYS structures can be exported to a spm-file in state space form after a modal analysis. The file contains the following state space matrices<sup>2</sup>:

System matrix A with the eigenvalues. States are modal coordinates.

Control matrix B containing components of the eigenvectors at the input to the system (forces).

Observer matrix C containing components of the eigenvectors at the output (displacements).

The state space matrices in the spm-files (Simplorer SML format without reference) can directly be imported to MADYN 2000 as a DBS (dynamic bearing support). The procedure is described in the following.

Clicking on a “+” button at SBS locations opens the usual drop down menu with options to create a DBS. The button corresponding to the first input of the state space system should be clicked first. Selecting “Create State-Space Model” opens a dialog to load a state space system. The button “File” starts a dialog to import a file. Among the files, which can be loaded the new option “States Space Model from Text File (\*.spm)” exists as shown in figure 5.1. After a spm-file has been selected, the window in figure 5.2 is opened with the state space matrices and the new edit-fields for the definition of the units in the spm-file and a structural damping. The system matrix A is then adapted accordingly. The matrix in the spm-file does not contain any damping.

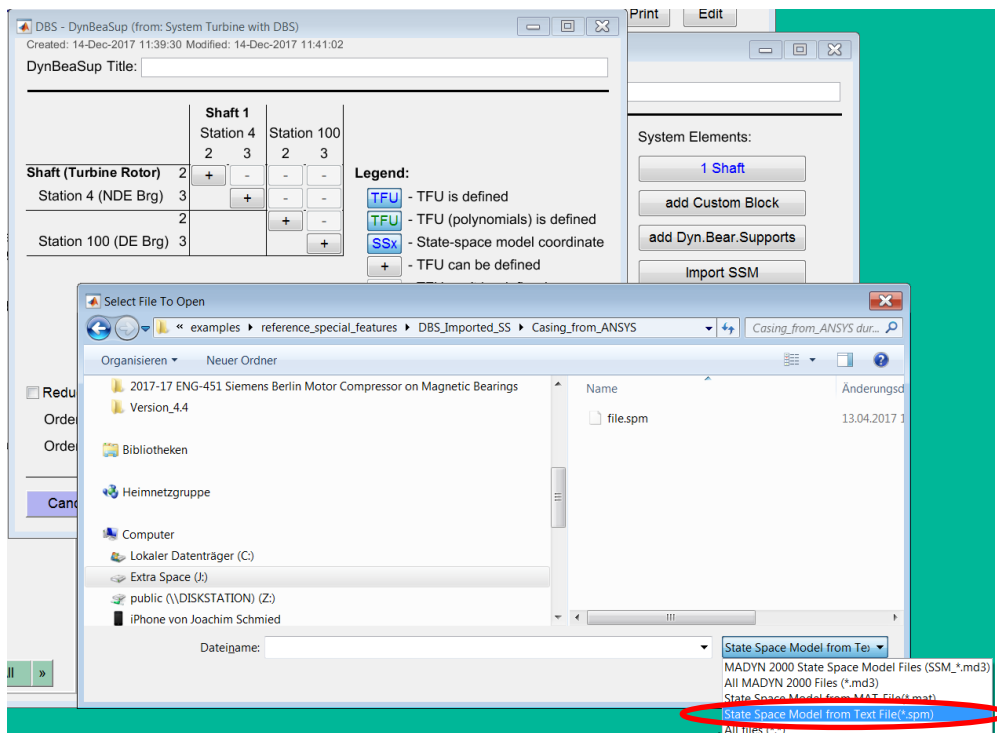


Fig. 5.1: Loading a state space system from an ANSYS spm-file

<sup>2</sup> In the paper [http://www.delta-js.ch/file/352/SIRM2013\\_Berlin\\_Alstom\\_ABS-235.pdf](http://www.delta-js.ch/file/352/SIRM2013_Berlin_Alstom_ABS-235.pdf) the state space matrices as a result of a modal analysis are described in equation (11).



- 30 -

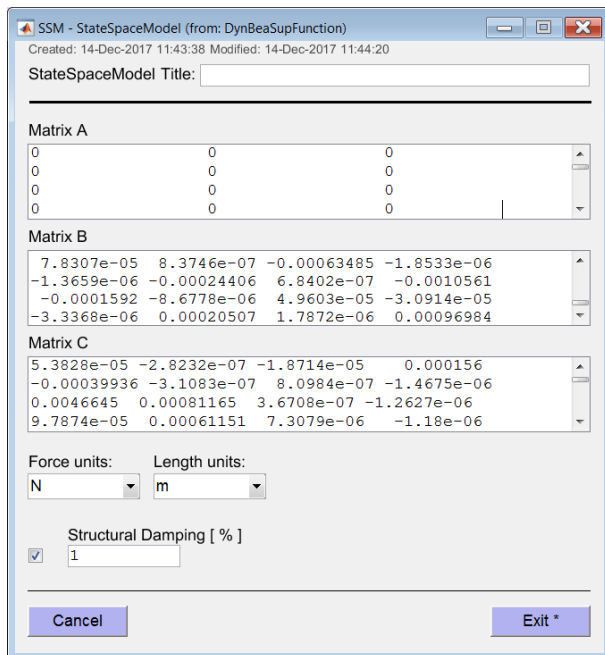


Fig. 5.2: Window with state space matrices A,B,C and controls to define the unit and structural damping

After exiting the window in figure 5.2 the DBS contains the matrices and the next steps are the same as for any DBS with a state space system. The other “+” buttons in the window (see figure 5.3) must be clicked in the sequence corresponding to inputs and outputs of the state space system. The numbers of inputs and outputs as well as the sequence in the DBS GUI have to be according to the imported matrices. If this is not the case an error message appears.

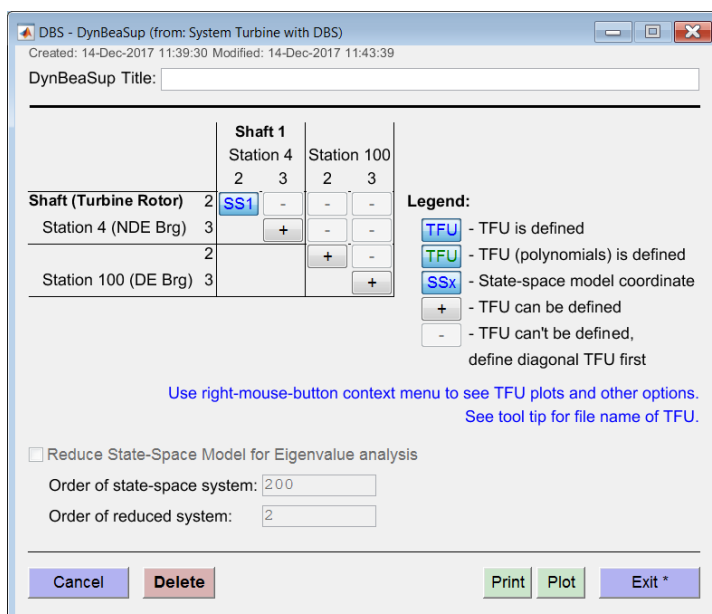


Fig. 5.3: DBS GUI after import of a state space system



- 31 -

## 5.2 Import of CAD Files

A possibility to import CAD file is offered in version 4.4. When loading a shaft CAD files can be selected as shown in figure 5.4. The CAD model should be a 2D axis-symmetric model with the x-axis as the rotor axis.

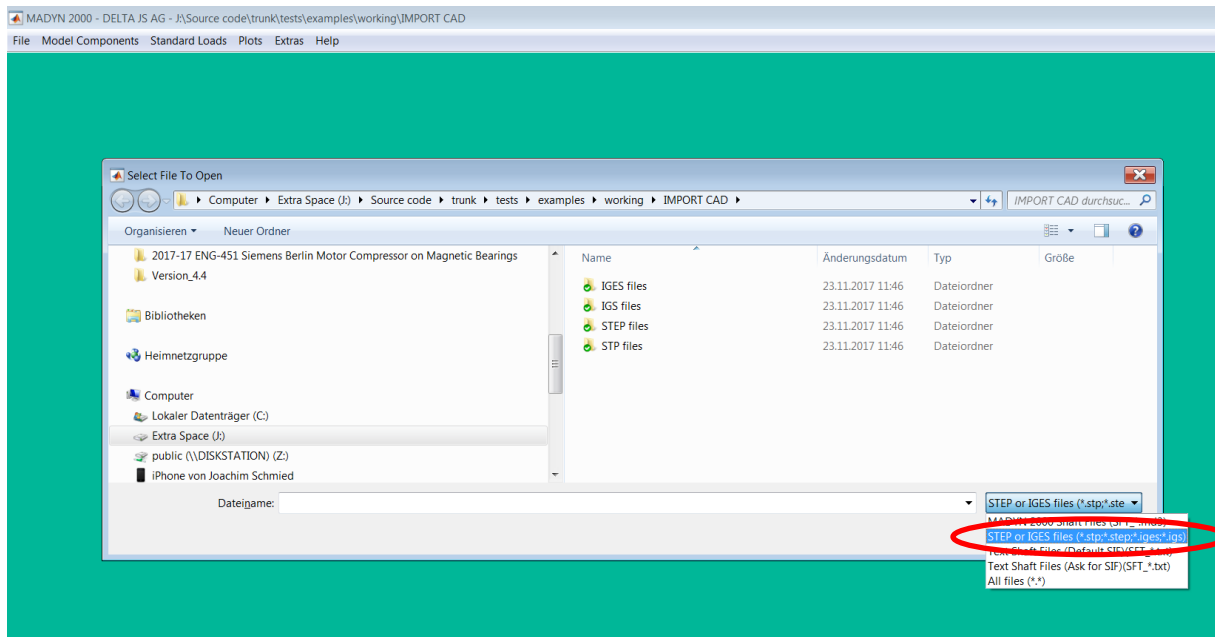


Fig. 5.4: Import of CAD files

There is a big variety of CAD models and the feature as implemented in version 4.4 is a first step for importing CAD files. For clear 2D axis-symmetric models it works well. For the import of very complex models the feature will have to be further developed in order to provide useful MADYN 2000 models with a reasonable number of degrees of freedom.



## 6. Further Improvements

### 6.1 Gear Springs

The sign of gear springs is now clearly defined: A compressive force has positive sign and a tensile force has negative sign. This has relevant for the assessment if there is loss of gear mesh contact. A negative force indicates a contact loss. To consider mesh with contact loss correctly in dynamic analyses requires a nonlinear analysis.

### 6.2 Shaft Plots

The shaft material plot could so far only make a difference between different materials, if they had different names. Materials with the same name and different properties were drawn in the same colour. In version 4.4 they are drawn in different colours, even if they have the same name.

Reduced stations are now visualized in a shaft plot by light grey lines. Unreduced stations are shown as black lines. An example with many reduced sections can be seen in figure 6.1.

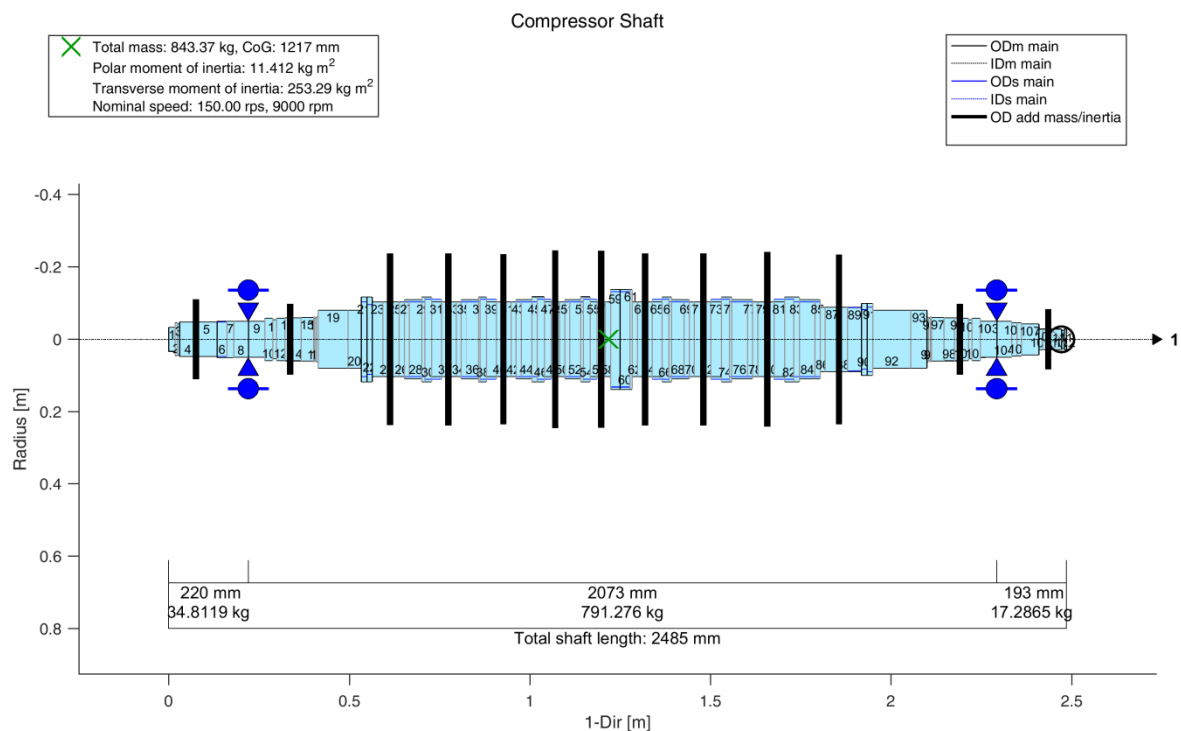


Fig. 6.1: Shaft plot with many reduced sections