iSTRDYN© - *integrated Stress, Thermal, and Rotor Dynamics*

Power Turbine Analysis Example

***iSTRDYN* Modeling, Solutions, and Result Processing**

DynaTech SOFTWARE LLC

July 2007

This presentation shows a typical analysis sequence using *iSTRDYN*. A generic power turbine rotor is imported, meshed, and analyzed for temperatures, stresses, and rotor dynamic response. Both linear and non-linear supports are used.

DynaTech
SOFTWARE LLC

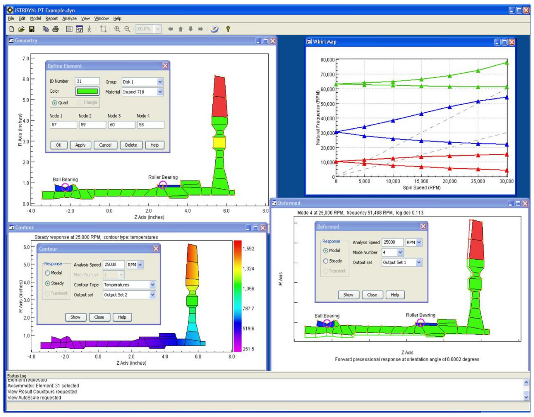
Description of Example Analysis

- **Import of CAD file, creation of geometry**
- **Generation of 2D finite element mesh**
- **Heat transfer – temperatures at various speeds**
- **Elastic stress analysis due to speed**
- **Linear natural frequency calculation**
- **Linear unbalance response**
- **Calculation of rolling element bearing properties and effect on unbalance and natural frequencies**

- 2 -

This example analysis starts with a CAD file of the cross section, then creates a mesh for use in the analysis. Heat transfer, stress, and rotor dynamic response are illustrated. The application of non-linear rolling element bearings is highlighted, showing the difference between assumed and calculated bearing properties. This is a typical example of analyzing a rotor configuration to determine if the design is feasible.

Modern, Platform Independent Interface



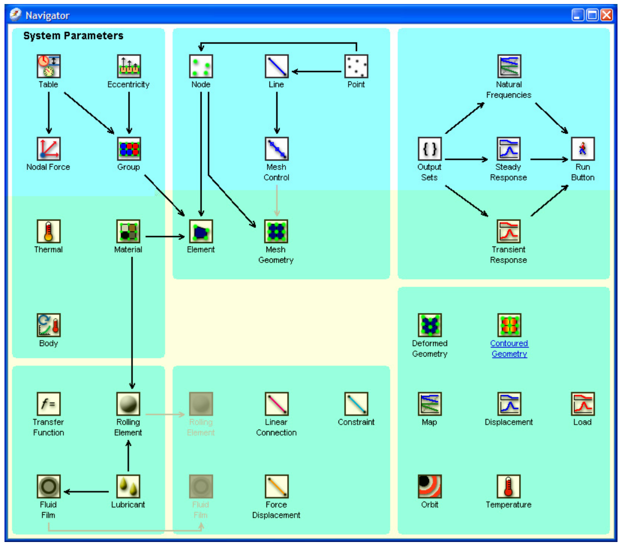
- User selectable graphical environment
- Desktop, LAN, & Internet versions
- Extensive data import using XML
- Report & plot export
- English & SI units
- Expert user assistance
- Context sensitive help files

- 3 -

iSTRDYN uses a modern, windowed interface for all definition, analysis, and review. It runs on many different computing platforms, including Windows, Unix, Linux, and MacIntosh. Import and export is accomplished with XML, text, or graphics format (such as JPEG) files. Great care has been taken to fully inform the user as to what units are being used for all definition and output, and three systems are supported – English, SI-meters, and SI-millimeters. Parts of the model can be defined, displayed, and reviewed in one system and then switched for other information. The expert system and help system are essentially secondary programs that can be opened and used for reference during analysis sessions.

DynaTech SOFTWARE LLC

Graphical Flowpath with Navigator

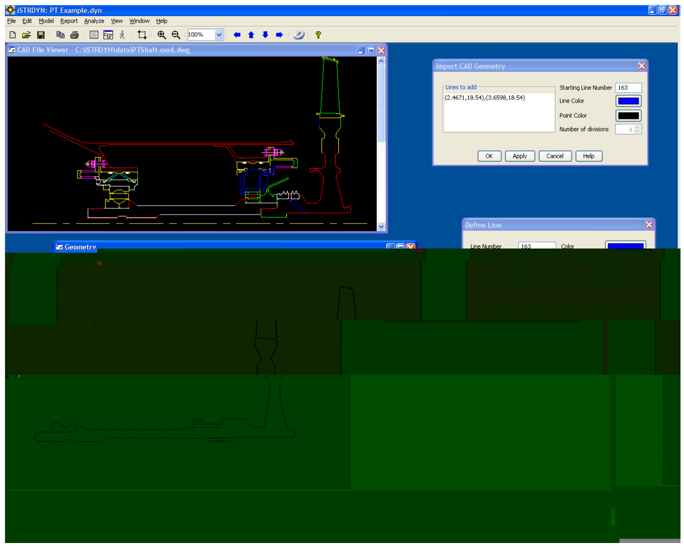


- 4 -

The expert system uses a graphical "flowpath" to inform the user of what options are available and what needs to be defined in order for a particular analysis to be run. This interface is called the Navigator. All definition, analysis specification, execution, and results review can be performed from this interface. The various icons will be "greyed-out" when the particular option is not available. Moving the cursor over these unavailable options will provide an explanation of what is needed in order to use that feature. This hierarchy of options is also present in the main interface, in that the various menu commands are only available if data or results are present.

DynaTech SOFTWARE LLC

CAD File Import & Geometry



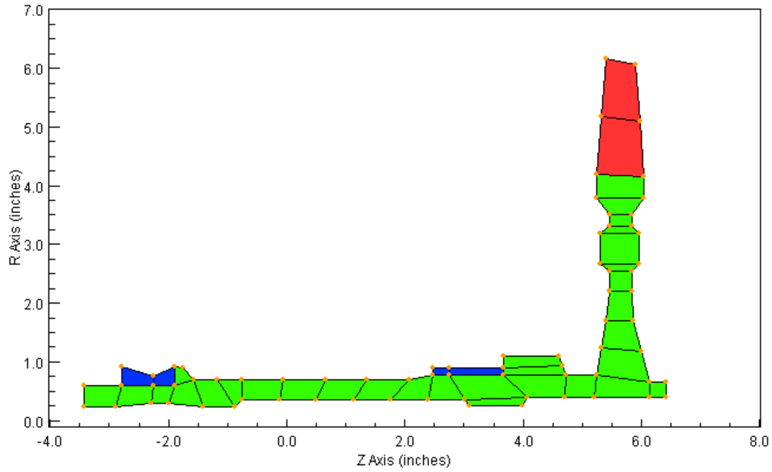
- 5 -

This screen shot shows the CAD import window, the resulting point and line geometrical description obtained from the CAD data, and two dialog boxes used for the import and definition. The CAD file importer requires 2D data, and will read files in 200+ 2D/vector formats such as AutoCAD, Solidworks, Pro/E, MicroStation, ME10, HPGL, Visio, ... , just about any current CAD program. Once the CAD data is read and geometry created, the lines can be sectioned into areas and automatically meshed.

The particular rotor presented in this example is a representative power turbine, consisting of a two-bearing shaft and single turbine wheel. For a rotor of this size, the maximum speed would be approximately 30,000 rpm (otherwise tip speeds would be too high).

DynaTech SOFTWARE LLC

Generate Mesh



72 nodes, 37 elements (2 bladed), 7.6 kg (16.7 lbm)

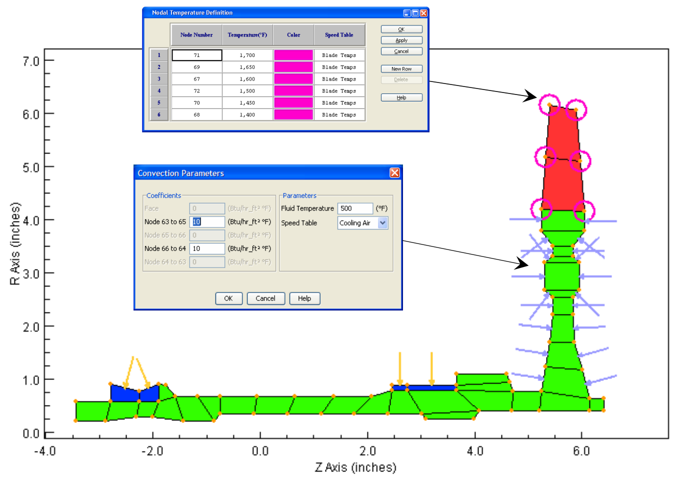
- 6 -

This geometry plot illustrates the 2D axisymmetric model generated from the CAD file import. The various lines were broken into areas, divisions were set, and then the auto-mesher was used to define nodes and elements. If the line geometry is broken into appropriate areas, the entire model can be meshed with a *single* command! For this particular example, that was not possible because the two red elements are bladed, with the thickness at the nodes defined directly. The thickness can also be specified using a 2D table.

The mesh used in this example contains 72 nodes and 37 elements. The exact numbering of these nodes and elements is not important, as the program does a profile sort prior to performing any calculations. The colors of the nodes and elements are user selectable from a palette of available colors. In this plot, the turbine blades and the elements at the two bearing locations have been selected to have different colors from the rest of the model. The actual numbers can be displayed, or as in this pictures, hidden from view, using a viewing option dialog. With the various options for supports, loads, and displays, the particular element or node can be graphically “picked” from the mesh.

DynaTech SOFTWARE LLC

Heat Transfer Boundaries



Tables summary

Total number of Tables:3

Label	Scale Factor	Table Type
Blade Temps	1.0000	Speed

Speed (RPM)	Value
0.0	0.2450
5,000	0.5670
10,000	0.7170
15,000	0.8170
20,000	0.8830
25,000	0.9500
30,000	1.0000

Label	Scale Factor	Table Type
Cooling Air	1.0000	Speed

Speed (RPM)	Value
0.0	0.5520
5,000	0.8060
10,000	0.8730
15,000	0.9180
20,000	0.9480
25,000	0.9780
30,000	1.0000

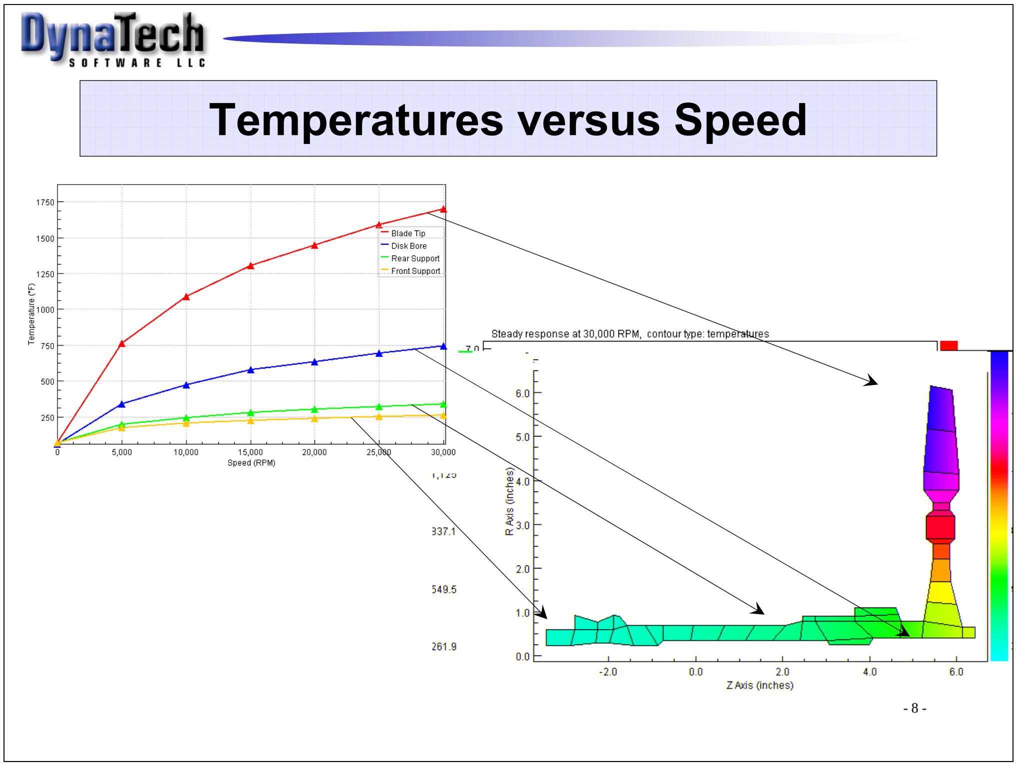
Label	Scale Factor	Table Type
Oil Temp	1.0000	Speed

Speed (RPM)	Value
0.0	0.7460
5,000	0.8900
10,000	0.9280
15,000	0.9540
20,000	0.9700
25,000	0.9870
30,000	1.0000

- 7 -

The first analysis that will be performed is heat transfer. There are two boundary conditions being placed on the rotor. With the turbine wheel blades, specified temperatures are being used, since the heat transfer conditions are well known for these airfoils. With the web of the disk, and at the two bearing positions, convection boundary conditions are applied. All of these conditions are graphically displayed by the arrows pointing at the particular element surface or a circle around the prescribed nodal temperature. Another boundary that could be used but is not in this example is heat generation.

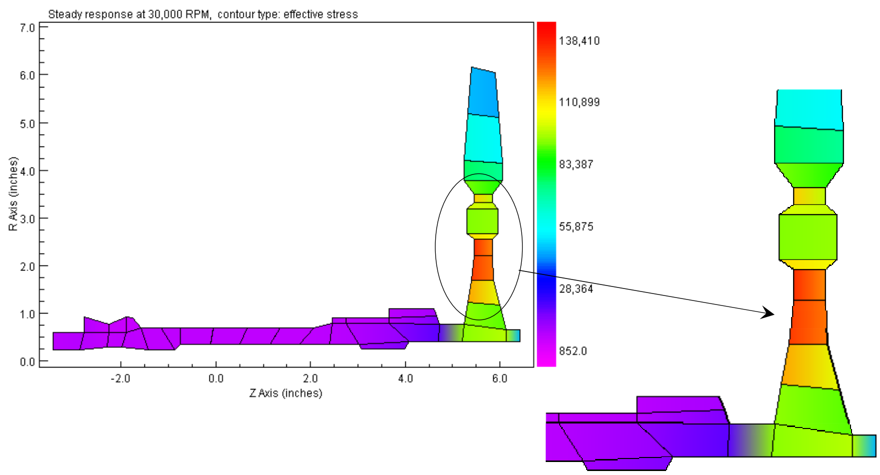
Note that all of the boundaries have a “Speed Table” associated with the definition. The contents of these tables is listed on the right. This feature allows the boundary to be specified at a particular speed, in this example at full speed, and then the tables are used to ratio the value at other speeds during the calculation.



Results from the steady (speed) response heat transfer calculation is displayed in two ways. First, several nodes have been selected and the temperature as a function of speed has been plotted. Second, a contour diagram shows the entire rotor temperature distribution at maximum speed. From these plots, it is observed that the roller bearing area of the shaft is running very warm, probably too hot for a good design.

DynaTech SOFTWARE LLC

Stresses From Rotation



- 9 -

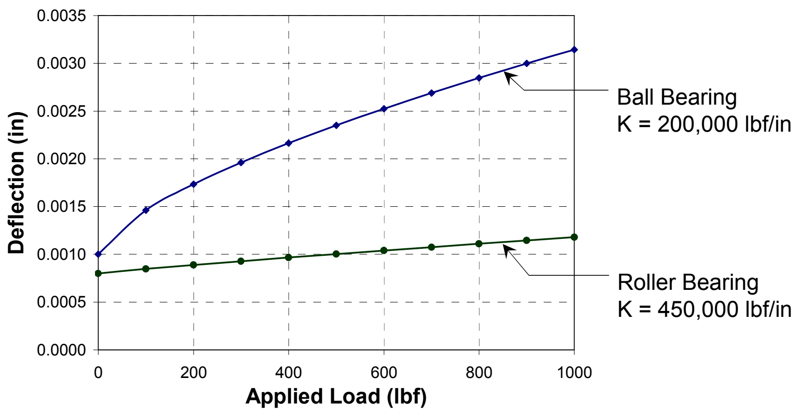
Stresses can be obtained from any response calculation – natural frequencies, symmetric and non-symmetric steady (speed-dependent) loads, and from transient (time-dependent) calculations. This particular plot displays the effective (Von Mises) stress in the rotor at maximum speed and including temperatures. A particular section of the turbine disk is showing relatively high stress, probably excessive for the particular temperature. The overall plot has been zoomed to provide more detail. Obviously, if this was a design analysis, additional calculations would probably be stopped until this stress situation was handled. If the mesh needs to be changed, such as to add more thickness, this can easily be done by going to the geometry display, picking the desired nodes, and changing the location.

DynaTech SOFTWARE LLC

Bearing Stiffness Estimates

6208 angular contact bearing
Ball size: 9 x 11.91 mm (0.469 in)
Pitch diameter: 61.20 mm (2.409 in)
Diametral clearance: 0.051 mm (0.002 in)
Inner/Outer curvature factor: 0.525/0.525

209 cylindrical roller bearing
Roller size: 14 x 10.0 mm (0.394 in)
Pitch diameter: 65.0 mm (2.559 in)
Diametral clearance: 0.041 mm (0.0016 in)
Roller effective length: 9.5 mm (0.374 in)

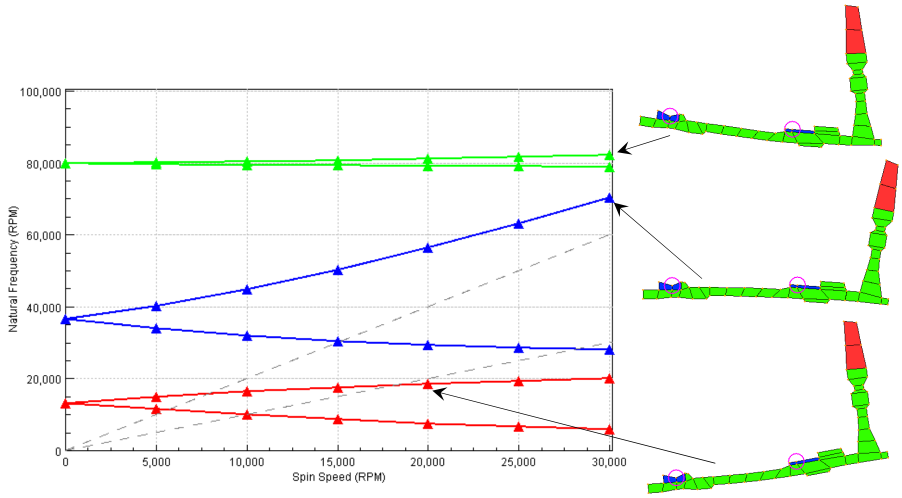


- 10 -

This chart shows a Hertzian contact load-deflection analysis for both bearings. The deflection considers the specified diametral clearance. Dividing the applied load by the combined deflection (clearance plus contact) a stiffness is calculated, which is obviously a function of load. Taking average values, the ball bearing stiffness is 200,000 lbf/in, and the roller is 450,000 lbf/in. Note that with the dimensions given for the bearings, the 6208 ball bearing bore is 40 mm (1.575 in), OD is 80 mm (3.150 in), and width is 18 mm (0.709 in), and the 209 roller bearing bore is 45 mm (1.772 in), OD is 85 mm (3.346 in), and width is 19 mm (0.748 in), all of which are standard dimensions. This geometry, along with the data in the chart, is used as input to the non-linear iteration which will be presented in a later chart.

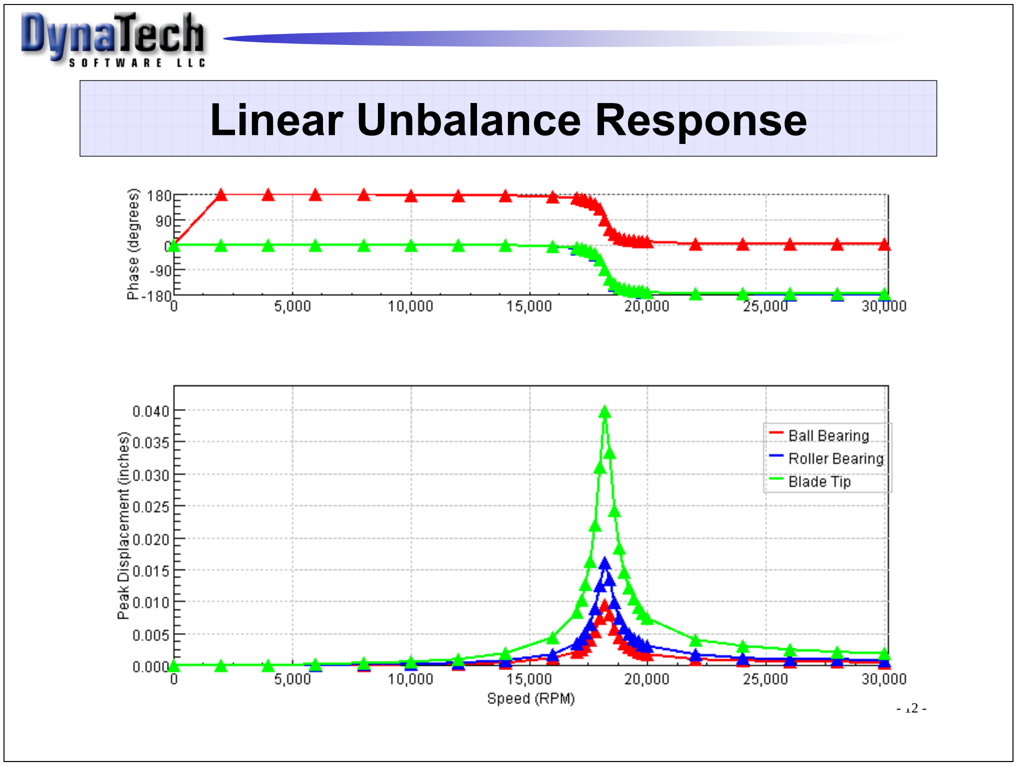
DynaTech SOFTWARE LLC

Linear Natural Frequencies



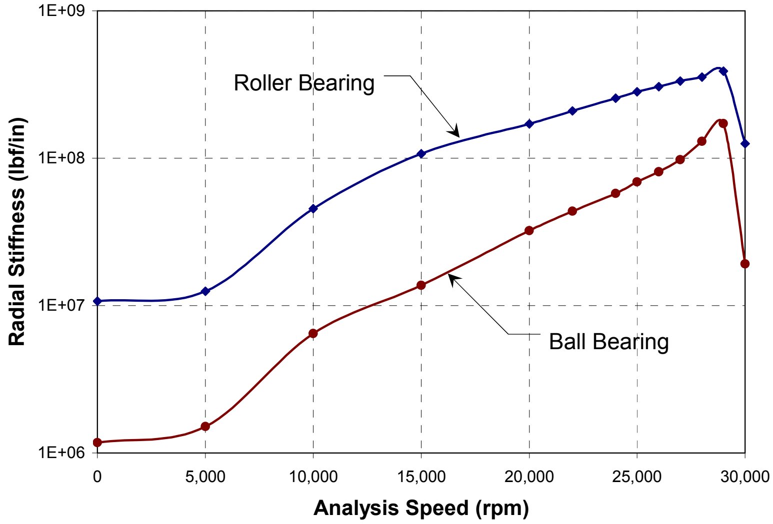
- 11 -

This whirl map and associated modes display the natural frequency characteristics of the linear model. Three modes are displayed, the first of which is controlled by the roller bearing stiffness, the second is the bending mode of the overhung turbine (including flexing of the disk), and the third is a combined mode of shaft bending and ball bearing motion. In the operating range of this example, a single critical speed is predicted, at approximately 18,000 rpm.



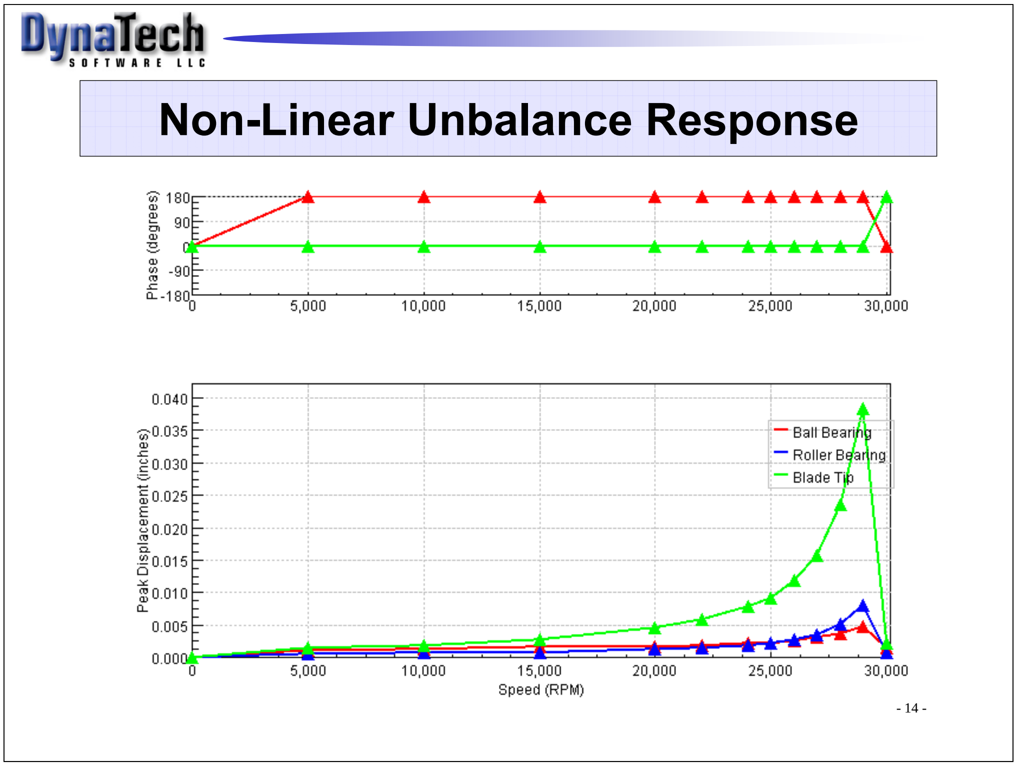
This shows the deflection of the rotor at three locations – the two bearing locations and the top of the turbine. The motion is very sharp because of the low amount of damping assumed for the bearings, in this case 2% of critical. The shape of the response peak is very classical and symmetric, typical linear behavior, as predicted from the whirl map. Note that peak response was obtained by running a refined speed increment after the coarse overall analysis was calculated and examined. These two runs were stored in different Output Sets, one of the unique features in *iSTRDYN*.

Non-Linear Rolling Element Bearings

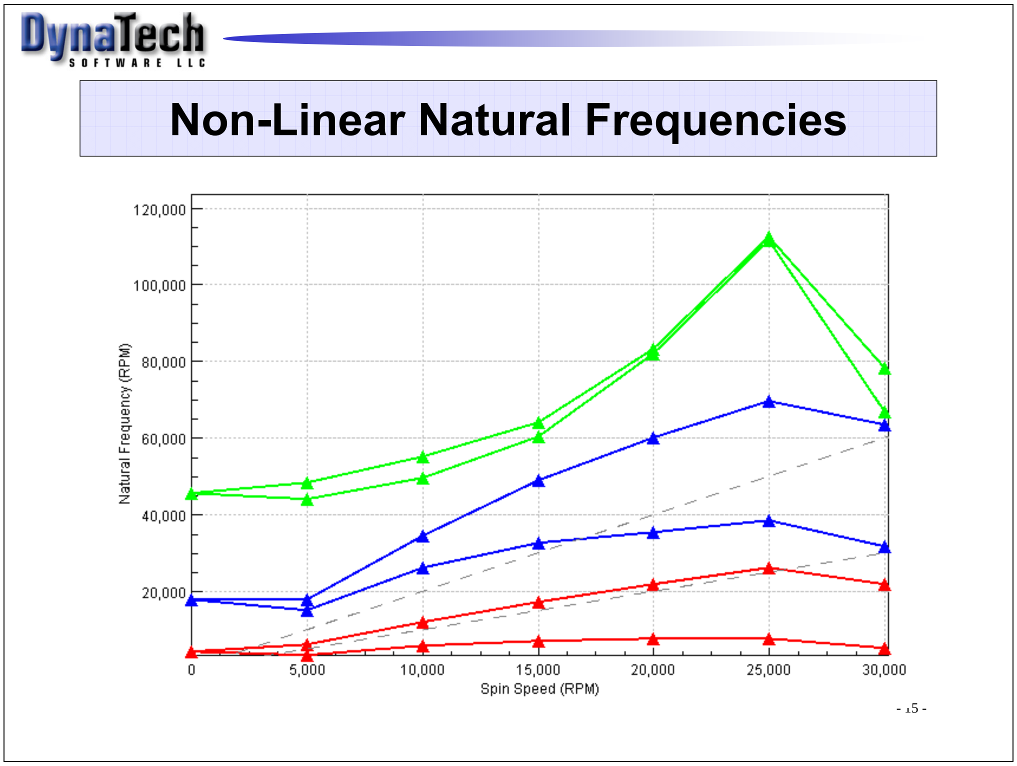


- 13 -

Replacing the two linear bearing supports with non-linear rolling elements, a significantly different response is obtained. This chart shows the calculated stiffness of the two rolling element bearings as a function of speed. The stiffness determined in the iteration is available in the report menu, which also includes details about each individual element loading and overall bearing fatigue life. In contrast to the linear coefficients, the actual bearing stiffness for this example changes by more than an order of magnitude, and for the ball bearing, by two decades. This substantial change is partially due to running through a critical speed, but in general, it is obviously inaccurate to assume rolling element bearings are constant stiffness supports.



The non-linear response produced by the iterative calculation of the ball and roller bearing dynamic properties shows a critical speed at 29,000 rpm, which for a 30,000 rpm design is extremely undesirable. Note that the response starts to gradually build at 15,000 rpm, then continues to increase all the way to 29,000 rpm, which is a hardening response. The non-linear behavior of the bearings is consistent with the load-deflection characteristics and is obviously not predicted by linear assumptions. Notice the peak deflection at each bearing is roughly half that of the linear case, even though the critical speed is 10,000 rpm higher.



Compared to the linear whirl map, the non-linear map is very unusual. The primary characteristic is the confirmation of the hardening response with the roller bearing. Notice the first mode is "tracking" the 1/rev excitation line, and then at a speed above 25,000 rpm, the mode crosses the 1E line to generate a critical speed. The gradually increasing stiffness of the bearings also drives the second and third modes to high frequencies until the critical speed is reached. This analysis was produced after the non-linear bearing iteration was complete, so the stiffness values are relative to the exact speed and loading conditions.

DynaTech SOFTWARE LLC

Revolutionary Analysis Paradigm Shift

- **Principal mechanical design factors now integrated**
  - **Heat Transfer**
  - **Stress**
  - **Rotor Dynamics**
- **Direct evaluation of key boundary conditions**
  - **User specifies geometry and properties**
  - **Code determines properties from calculated deflections**
- **Improved accuracy and understanding**
  - **Non-linear analysis substantially different than linear**
  - **Stresses and temperatures show problems with design**
  - **Integrated analysis removes estimates and assumptions**

- 16 -

Although this example shows just a fraction of the capabilities in *iSTRDYN*, the integrated mechanical design features allow an unprecedented feasibility evaluation of a typical rotor-bearing system. The most significant effect highlighted is the difference between assumed rolling element bearing stiffness and actual speed-displacement dependent calculations, which dramatically shifts a critical speed. The heat transfer and stress results also show there are cooling and stress problems with this design, which can be handled directly by *iSTRDYN*, rather than having to use other codes. Obviously, *iSTRDYN* is ideally suited for conducting the analysis of a rotor-bearing system, and with the direct evaluation of previously assumed support properties, improves the accuracy of the analysis as well as providing additional insight into the performance of the machine.