ORBIS

Modern Rolling-Element Bearing Analysis Software

USER'S MANUAL

Updated for Version 2.4.1
7-Nov-2015

Table of Contents

Table of Figures

Table of Tables

1.0 Getting Started

1.1 System Requirements

The following minimum system requirements are needed to run ORBIS.

- Windows family operating system (note: ORBIS has not yet been validated on Windows 10 but is expected to work)
- Display monitor with minimum resolution of 1024 by 768 pixels
- 128 MB of free disk space
- 256 MB RAM
- Available USB port
- Java 6.0 or greater (see below for more details)

1.2 Installation Instructions

Run the automated installer steps below to complete installation. Administrator rights are needed to complete the installation properly. Note: ORBIS will install to 'All Users' on a given machine.

1. Insert the installation CD and navigate to your CD directory.
2. Double click the ***Setup.exe***
3. Follow installer instructions to complete installation.

1.3 Java Runtime Environment

In order for the software to run properly, the host computer must have Java Runtime Environment (JRE) version 6.0 or greater installed. The JRE is an industry standard and will generally already be installed on most modern computers. If your computer does not have JRE 6.0 or greater already installed you may install the version included from the installation directory or download the latest version from the Sun/Oracle website (www.oracle.com). To install the version included from the ORBIS CD follow these steps.

1. Open the Java folder on the CD (\\ORBIS\Java\)
2. Double click ***jre-6uXX-windows-i586-s.exe*** to install on Windows platforms (Windows 7, Vista, Windows XP, Windows 2000, Windows 2003, and Windows 2008 Server). Note: the 'XX' in the filename denotes the particular update to the JRE Version 6.

1.4 Coordinate Systems

ORBIS uses a standard right handed coordinate system for all loads and deflections. As shown in the figure below, the x-axis is aligned with the shaft spin axis, with positive pointing rightward on the page, and the positive y-axis is defined as pointing upward on the page. Positive moments/rotations follow right hand rule along respective axes.

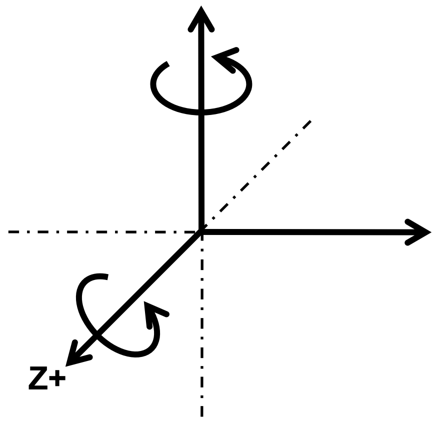


Figure 1. Coordinate System

1.5 Numerical Input Formatting

Most inputs required to perform an analysis will be numeric. ORBIS accepts multiple different methods of numerical inputs but there are a few that are not allowed. The table below shows examples of valid and invalid numeric input formatting.

Table 1. Numeric Formatting Examples

Valid Inputs	Invalid Inputs	Description
1000	1,000	Comma notation is not allowed
+1000		
-1000		
1.0e3	1.0e 3	Spaces anywhere within the input string are not allowed
1.0e+3		
1E3		
1E+3		
0.001		
.001		
1.0e-3		
1E-3		

2.0 User Interfaces

2.1 Main Graphical Interface

The main graphical interface is the primary window within ORBIS. This window allows the user to define their bearing system and perform a majority of common analysis runs. As shown in the figure below this window is organized into five regions.

- **System Inputs** – located in the upper left region, is where external loading, temperatures, shaft/housing materials and lubricants are defined.
- **Dynamic Analysis** – located in the lower left, is where parameters such as velocities, fatigue life (reliability and life factor), viscous torque factor, rotational member and load fixity are defined.
- **System Display** – located in the upper right, provides an engineering sketch based on the user defined system.
- **Bearing Row Inputs** – located in the lower right, is where all pertinent parameters for defining configuration of each bearing row in the system, such as row location, housing/shaft fits, preload, contact angle orientation, etc.
- **Input Field Description** – located bottom center, provides key details and helpful information for each input field. Upon placing the cursor within a given input field applicable information is displayed in the Input Field Description area.

See subsequent sections for details about each input field in the main graphical interface. To submit an analysis the user simply selects the Analyze button at the bottom of the window. Analysis results will appear in a new window. See section 2.3 for a description on the Results window and section 4.0 for a detailed description of each output parameter.

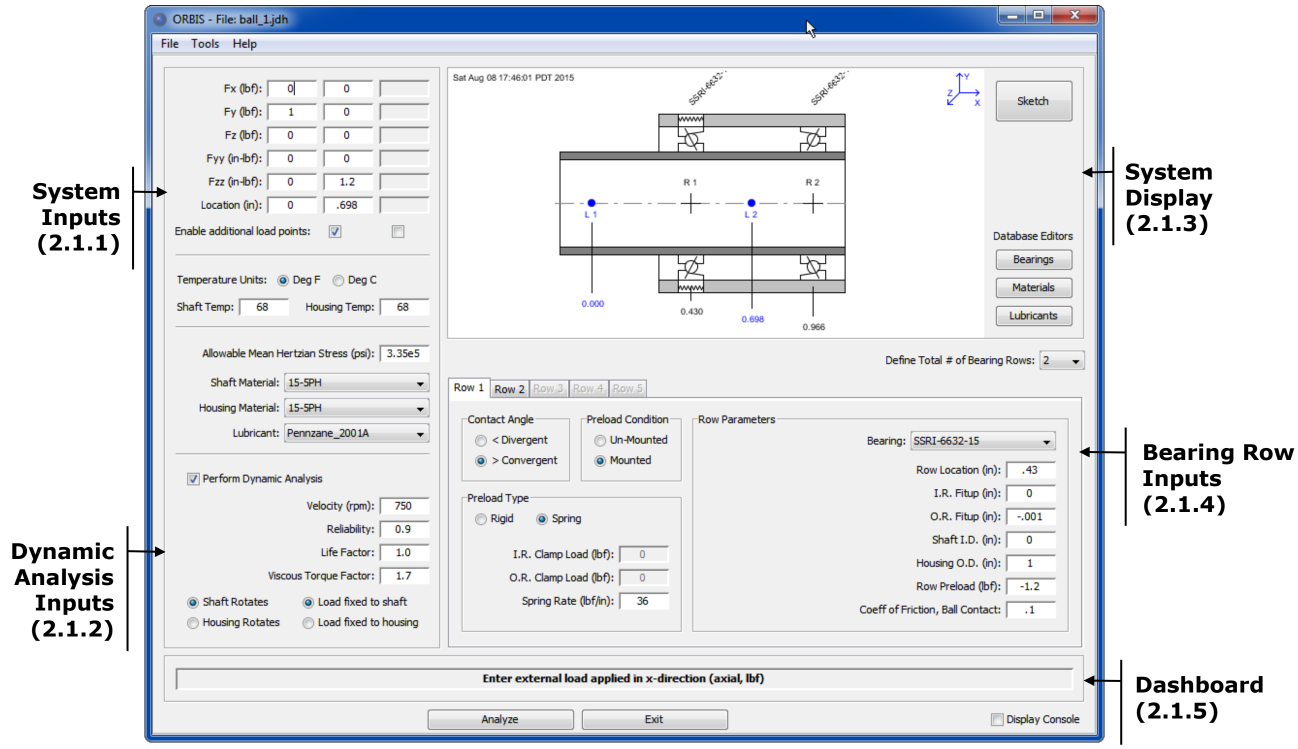
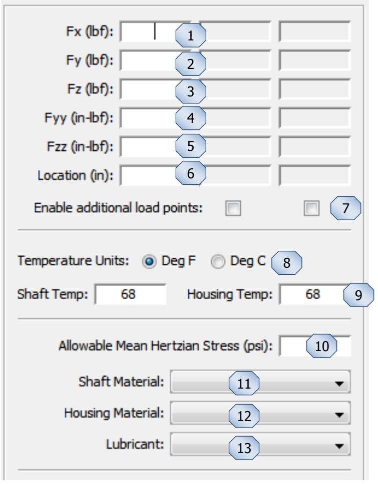


Figure 2. Main Graphical Interface

2.1.1 System Inputs

The System Inputs area is where external loading and housing/shaft material definitions are defined. See the following figure for descriptions of each input field.

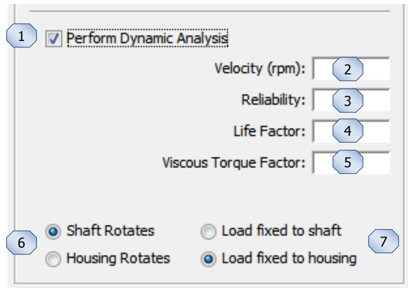


#	Title	Description
1	Fx (lbf)	External axial load components for up to three load points (positive is toward the right).
2	Fy (lbf)	External radial load components for up to three load points (positive is upwards).
3	Fz (lbf)	External radial load components for up to three load points (positive is out of the page).
4	Fyy (in-lbf)	External moments about the Y-Axis for up to three load points.
5	Fzz (in-lbf)	External moments about the Z-Axis for up to three load points.
6	Load Location (in)	Location of external load points (along X-Axis).
7	Enable additional load points	Checkboxes for second and third load points. Select checkboxes to enable load component inputs.
8	Temperature Units	Radio button toggles between Fahrenheit and Celsius units.
9	Shaft/Housing Temp (F)	Bulk temperatures of the shaft and housing.
10	Allowable Mean Hertzian Stress (psi)	Allows user to specify an allowable contact stress. All elements with contact stress above the specified allowable will be highlighted in the output file.
11	Shaft Material	Allows user to assign shaft material from the material database.
12	Housing Material	Allows user to assign housing material from the material database.
13	Lubricant	Allows user to assign lubricant to all bearing rows from the lubricant database.

Figure 3. System Inputs

2.1.2 Dynamic Analysis Inputs

ORBIS offers both static and dynamic analysis modes. Static mode is useful for simple slow speed applications where dynamic effects are negligible. The static solver is also quicker due to the reduction in parameters required to converge. Dynamic analysis mode provides full analysis output parameters (such as torque, fatigue life, film parameters, centrifugal and gyroscopic forces, etcetera). See the following figure for detailed descriptions of each input field.

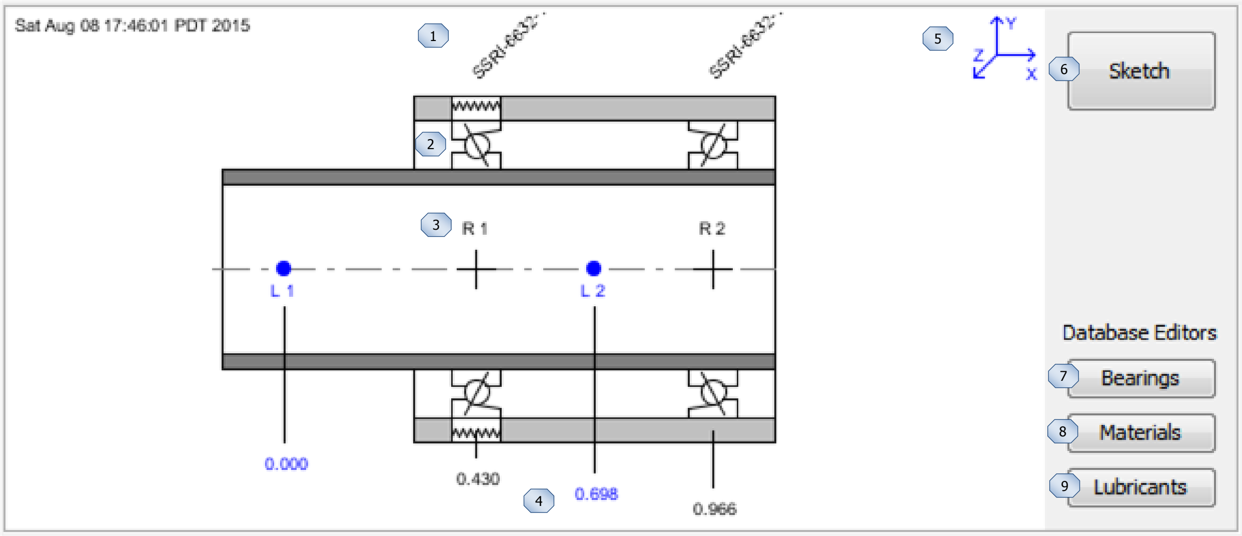


#	Title	Description
1	Dynamic Analysis Checkbox	Selection of this checkbox activates the dynamic analysis inputs below. Default is un-checked.
2	Velocity (rpm)	Defines the rotational velocity, in RPM, of the rotational member.
3	Reliability	Defines the reliability for fatigue life. Valid inputs are between 0 and 1, exclusive. Default is 0.9 (L10 equivalent).
4	Life Factor	Allows user to specify an overall combined life adjustment factor. ORBIS will compute reliability and lubricant regime adjustment factors; however other factors such as material and operating environment must be included here.
5	Viscous Torque Factor	Compensation factor for type of lubrication. Default is 1.7, which represents a reasonable initial guess for an oil lubricated ball bearing (no oil bath or jet conditions).
6	Rotational Member	Radio buttons allow user to specify either 'shaft rotates' or 'housing rotates.'
7	Loaded Member	Radio buttons allow user to specify whether load is fixed relative to the shaft or housing.

Figure 4. Dynamic Analysis Inputs

2.1.3 System Display

The system display area provides a proportional engineering sketch of the user defined system. Many key details about the user setup are identified within the sketch. To avoid setup mistakes, perhaps due to mistyped inputs, it is recommended to review this sketch prior to submitting an analysis. The system sketch is also copied and included in the results window as a figure. See the following figure for a detailed description of the information provided in the system display panel.



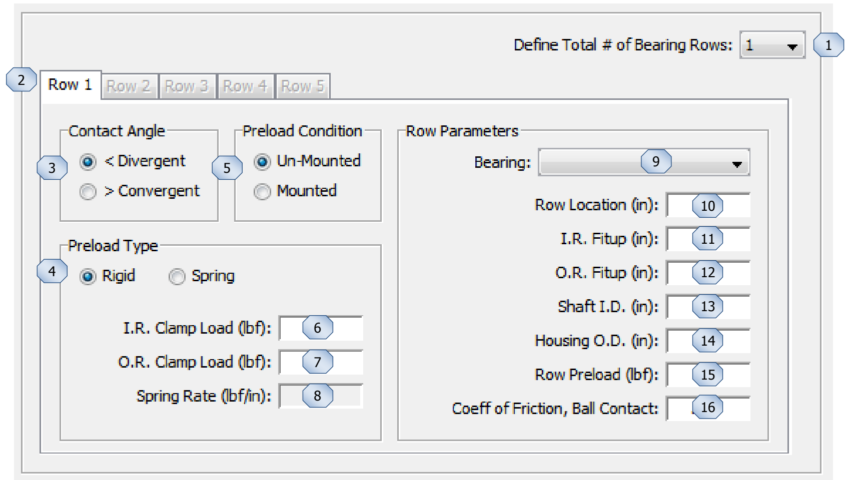
#	Title	Description
1	Upper Region	The upper region provides a date/time stamp and the names of each bearing in the system. Bearing names are as defined in the bearing database.Bearing sketches contain user defined contact angle orientation and any preload spring definitions.
2	Bearing Row	Each bearing row is sketched with the user defined contact angle orientation. Additionally, if the row floats on a spring there will be a spring adjacent to the row.
3	Inner Shaft	Each row and load point is given a unique ID that pertains to the corresponding entry field within the main window.
4	Lower Region	Axial locations (x-axis coordinate) of each load point and row location is shown here.
5	Coordinate System	Coordinate system is shown in upper right corner of sketch window.
6	Button – Sketch	Selecting the Sketch button refreshes the sketch window with current user-defined inputs.
7	Button – Bearings	Button opens the Bearing Database dialog window (see section 2.2.1).
8	Button – Materials	Button opens the Material Database dialog window (see section 2.2.2).
9	Button - Lubricants	Button opens the Lubricant Database dialog window (see section 2.2.3).

Figure 5. System Display

2.1.4 Bearing Row Inputs

The Bearing Row Input area is where the user defines necessary inputs for each bearing row in the system. See the following figure for a detailed description of each input type.

A common mistake for new users is improper sign convention on the 'Row Preload' field. The user must consider the orientation of the contact angle and specify an appropriate sign on the row preload input. Contact angles are defined using convergent and divergent terminology (see section 2.1.4.1 for details). These terms relate to whether the contact angle line of action converges or diverges toward the spin axis as you traverse along the positive x-axis (rightward along the spin axis). For example, the leftmost bearing in a duplex pair of bearings, configured in a back-to-back or DB orientation, has a divergent contact angle. If this bearing was preloaded normally there would be a residual force acting on the inner ring toward the right which is positive (X+) in ORBIS coordinates. Subsequently, the rightmost bearing in this hypothetical DB pair has a convergent contact angle and requires a preload force acting to the left, or negative in ORBIS coordinates, on the inner ring. Note: positive values entered within ORBIS do not require the prefix 'plus' sign.



#	Title	Description
1	# Bearing Rows	Drop-down selection allows up to 5 bearing rows to be specified. Row tabs (see #2) will be activated based on number of bearing rows selected here.
2	Row Tabs	Row tabs are activated based on the number of bearing rows selected. Selecting an active tab allows the user to define parameters for that row.
3	Contact Angle	Contact angle definition for active row. A divergent contact angle extends away from, or diverges, from the spin axis as you traverse in the positive direction along the x-axis.
4	Preload Type	Specification for type of preloading. Options are rigid or spring. Rigid preloading activates input fields for inner and outer ring clamping forces. Spring preloading activates inputs for the spring rate.
5	Preload Condition	Specifies the condition at which the specified preload is defined. Un-mounted conditions means the rings are radially free at the specified preload. Mounted conditions apply the preload force based on the mounted fit-up conditions, which include changes to internal clearance from interference fitting and ring clamping.
6	I.R. Clamp Load (lbf)	Input field for the inner ring clamp load. Only active for rigid preload type.
7	O.R. Clamp Load (lbf)	Input field for the outer ring clamp load. Only active for rigid preload type.
8	Spring Rate (lbf/in)	Input field for the preload spring stiffness. Only active for spring preload type.
9	Bearing	Drop-down selection to assign the bearing for the active row. The drop-down menu will contain all bearings defined in the user defined bearing database.
10	Row Location (in)	Input field for the axial location (along x-axis) of the active bearing row.
11	I.R. Fitup (in)	Input field for the inner ring fitup to the shaft. Fitup is defined as the difference in the shaft O.D. to the free bearing I.D. A positive value indicates interference fits.
12	O.R. Fitup (in)	Input field for the outer ring fitup to the housing. Fitup is defined as the difference in the free bearing O.D. and the housing I.D. A positive value indicates interference fits.
13	Shaft I.D. (in)	Specifies the I.D. of a hollow shaft. For non-constant shaft wall thicknesses use the appropriate shaft I.D. at the bearing row location. For a solid shaft input a zero value.
14	Housing O.D. (in)	Specifies the O.D. of the housing. For non-constant housing wall thicknesses use the appropriate housing O.D. at the bearing row location.
15	Row Preload (lbf)	Specifies the preload force applied to the active bearing row. Preload forces are directional and must include the appropriate sign convention. To preload a bearing through its contact angle, standard preloading, specify a positive preload for divergent contact angles and a negative preload for convergent contact angles.
16	Coeff of Friction, Ball Contact	Specifies the rolling contact friction coefficient for the active bearing row.

Figure 6. Bearing Row Inputs

2.1.4.1 Contact Angle Orientation

Contact angle orientation is assigned within the bearing row input region, as discussed in the preceding section. Terminology for convergent and divergent is further illustrated in the figure below.

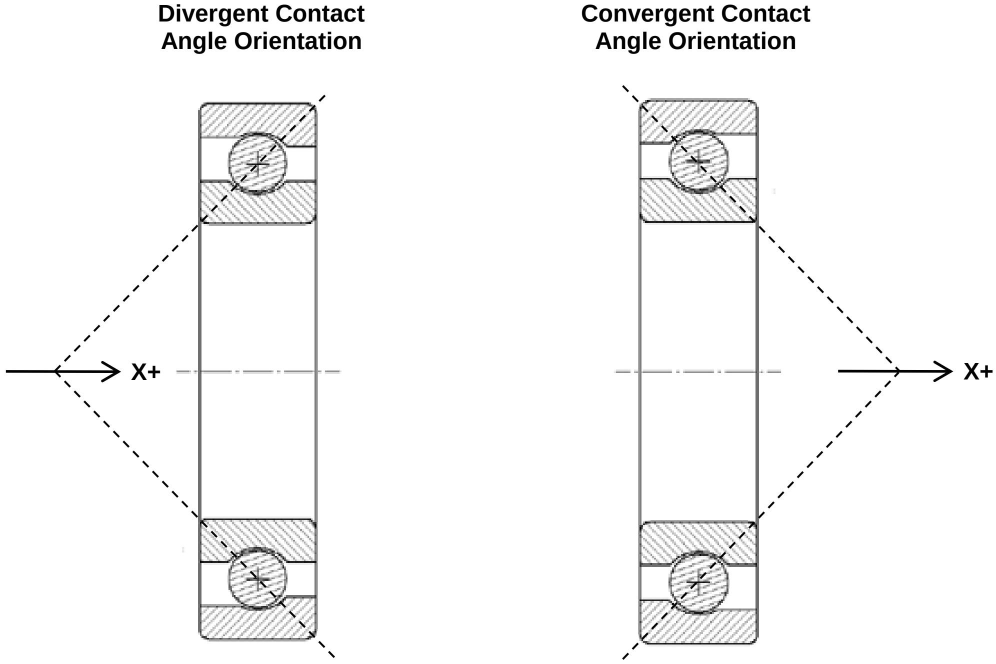
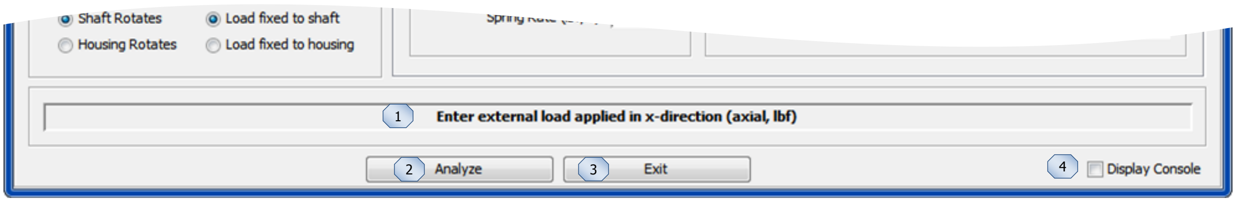


Figure 7. Convergent and Divergent Contact Angles

2.1.5 Dashboard

The dashboard area (lower portion of the main window) provides helpful user information and is also where completed setups are submitted for analysis. The following figure illustrates the various components of the dashboard area.



#	Title	Description
1	Input Field Description	The input field description bar provides helpful information to the user for each input field. When the user places their cursor in one of the input fields (done by clicking the mouse in a field or pressing the tab button to advance to the next input field) a description about that field appears in the Input Field description bar. Example shown pertains to the external load Fx (lbf) input field.
2	Analyze Button	The analyze button is used to submit the user setup for final analysis. Upon completion of an analysis the Results window (reference section 2.3) will automatically display.
3	Exit Button	Select this button to safely exit. User will be prompted to save any changes that have occurred to the active setup.
4	Display Console Checkbox	Selecting this checkbox will display the console window. See section 2.1.5.1 for further description of the console.

Figure 8. Dashboard Area

2.1.5.1 Console Window

The console window is used to display solver iteration messages. Information is automatically output to this window during each analysis submittal. Selecting the <clear> button at the bottom of the console window will erase all current contents of the console, otherwise text within the console is persistent and will remain available during the entire session.

Common information displayed to the console window is:

- Convergence criteria (see section 3.2)
- Norm of the residuals for each solver attempt
- Element contact loss at inner race
- Element equilibrium cannot be achieved
- Row expansions due to thermal loads exceed initial preload
- Number of iterations analyzed and if truncation is found when running a Worst Case Tolerance analysis
- Various step convergence information when running a Flexible Shaft analysis
- Confirmation of convergence

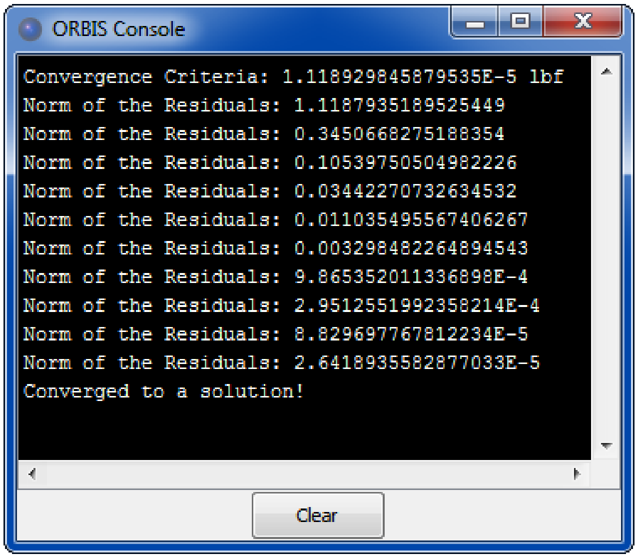
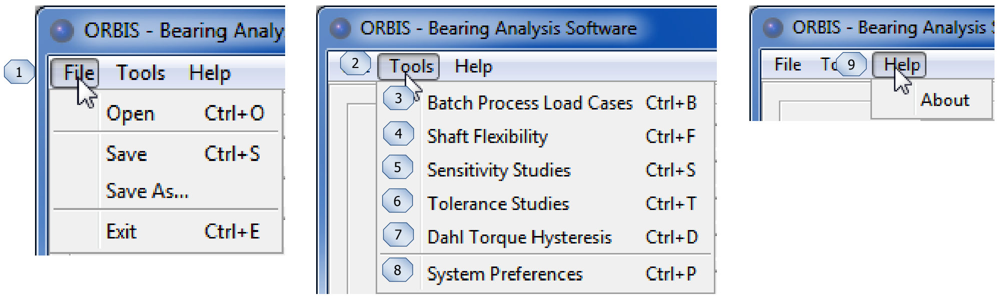


Figure 9. Console Window

2.1.6 User Menus

User menus are available within the main graphical interface. See the following figure for a detailed description of the available menu options.



#	Title	Description
1	File Menu	The file menu provides standard file options such as Open, Save, Save As and Exit. ORBIS maintains a unique file type that allows the user to save their bearing analysis setup.
2	Tools Menu	The tools menu provides advanced analysis utilities shown below.
3	Batch Process Load Cases	Selecting this utility allows the user to load a pre-configured comma delimited file with an unlimited number of load cases. Each load case is applied to the current defined bearing system and the results are saved to separate results files.
4	Shaft Flexibility	Selecting this menu option launches the Shaft Flexibility Analysis dialog. See section 2.4 for a detailed explanation of this dialog window.
5	Sensitivity Studies	Selecting this utility launches the Sensitivity Studies window. See section 2.5 for a detailed explanation of this dialog window.
6	Tolerance Studies	Selecting this utility launches the Tolerance Analysis window. See section 2.6 for a detailed explanation of this dialog window.
7	Dahl Torque Hysteresis	Selecting this menu launches the Dhal Torque Hysteresis window. See section 2.7 for a detailed explanation of this dialog window.
8	System Preferences	Selecting this utility launches the System Preferences window. See section 2.8 for a detailed explanation of this dialog window.
9	Help Menu	This menu provides an 'About' window to show key parameters regarding the current software version and lease expiration date.

Figure 10. User Menu's

2.2 Database Editors

ORBIS uses bearing, material and lubricant databases to define the majority of input parameters required in a standard bearing analysis. Once the user has defined their database entries they simply assign them to their analysis setup via drop-down menus within the main window.

Database editors allow the user to view, modify, add and delete bearing, material, and lubricant database definitions. The database editors are accessed from the buttons within the System Display area (see section 2.1.3).

Database definitions are stored in three specific files: Bearings.dat, Materials.dat and Lubricants.dat. These files are typically located within the ORBIS installation directory. However, database files can be placed anywhere, such as a shared network drive. In the case where multiple users have access to a common network drive it is recommended that a common set of database files be used for all users. See the System Preferences dialog (section 2.8) for details on how to import entries from external databases or change the default location of the database files.

It is important to maintain databases within ORBIS. As users begin to create and save various analyses the saved files depend upon database entries being available upon next use. For example, suppose a user creates a material definition titled "440C" and then defines a bearing named "XYZ Bearing" that uses the 440C material for the inner/outer rings and balls. Every time the user wants to run an analysis with XYZ

Bearings ORBIS will search the material database for a valid definition named "440C." If this name is not found ORBIS will generate an error message telling the user the material could not be found. This same situation occurs for all database entries and any user saved analysis setup files.

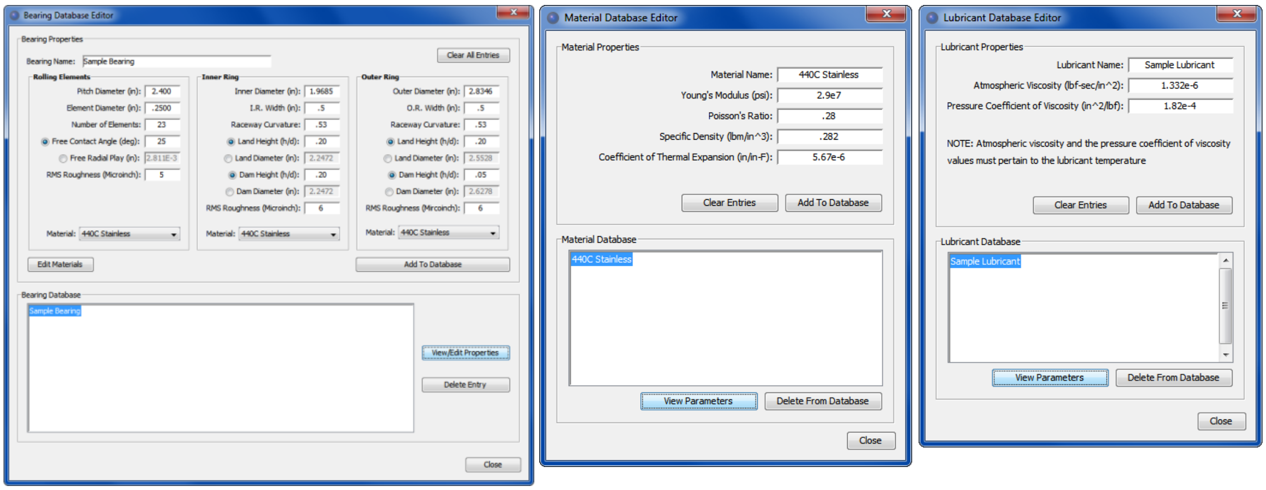
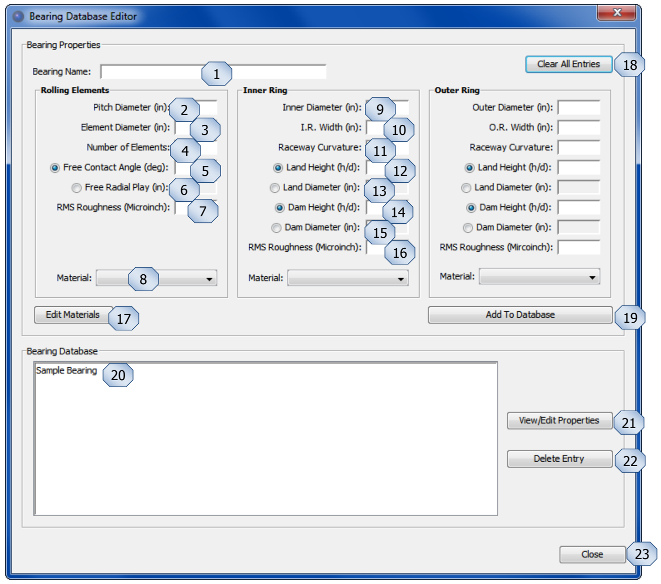


Figure 11. Database Editors

2.2.1 Bearing Database Editor

The Bearing Database Editor allows the user to add, edit, view or delete bearings to the database. See the following figure for a detailed description of the editor. Note that certain parameters may be defined in more than one way. For example, the free contact angle can be derived from the radial play, ball diameter and curvature ratios or input directly. Thus ORBIS allows the user to enter either set of information.

To edit existing database entries simply select the existing database entry and click the 'View Parameters' button. All entry fields are populated and the user can then make their changes. To shave the changes use the 'Add To Database' button. ORBIS will then ask to verify you want to overwrite the old entry with the new one. If you want to keep the old entries you must rename the new one with a unique name.



#	Title	Description
1	Bearing Name	Specify a name for the bearing.
2	Pitch Diameter (in)	Diameter that describes the rolling element centers (often the average between the bearing I.D. and O.D.)
3	Element Diameter (in)	Diameter of the ball.
4	Number of Elements	Number of balls in a single bearing row.
5	Free Contact Angle (deg)	Contact angle of bearing with no external loading. Must be a positive value. Only active when radio button is selected.
6	Free Radial Play (in)	Radial free play is synonymous with diametral play and represents the total linear travel, along a radial direction, the inner ring can move relative to the outer ring when axially unrestrained and negligible force is applied. Only active when radio button is selected.
7	RMS Roughness (micro-inch)	Surface roughness, RMS, of the ball.
8	Material	Assign materials from Material Database to the rolling elements, inner ring and outer ring.
9	Inner/Outer Diameter (in)	Bearing's inner or outer diameter.
10	I.R./O.R. Width (in)	Width along the bearing axis of the inner or outer ring.
11	Raceway Curvature	Raceway curvature of inner and outer rings, expressed as the ratio of the raceway radius to the ball diameter.
12	Land Height (h/d)	Height of the land diameter expressed as the ratio of the radial height to the ball diameter. The land is specified as the shoulder that contains the loaded contact zone. Only active when radio button is selected.
13	Land Diameter (in)	Diameter of inner or outer ring land. Only active when radio button is selected.
14	Dam Height (h/d)	Height of the dam diameter expressed as the ratio of the radial height to the ball diameter. The dam is specified as the shoulder that is unloaded, or opposite the contact angle.
15	Dam Diameter (in)	Diameter of inner or outer ring dam. Only active when radio button is selected.
16	RMS Roughness (Microinch)	Surface roughness, RMS, of the inner or outer raceway.
17	Edit Materials Button	Opens the Material Database Editor.
18	Clear All Entries Button	Clears all current input field entries. This does NOT clear the database entries.
19	Add To Database Button	Commits the specified input entries into the database under the bearing name specified. A warning will occur if the specified bearing name already exists within the database.
20	Database Entry	This are provides access to all current bearing names stored within the database.
21	View/Edit Properties Button	Once a database entry is selected within the database window, selecting this button will populate the bearing parameters into the input fields.
22	Delete Entry Button	With a database entry selected, this button will permanently delete the entry from the database.
23	Close Button	Closes the Bearing Database Editor.

Figure 12. Bearing Database Inputs

2.2.1.1 Shoulder Height Definitions

Land and dam heights, as discussed in the preceding section, can be defined as h/d ratios or diameters. The figure below illustrates an outer ring with the heights for the land (h_l) and the dam (h_d) identified. The term 'dam' refers to the non-contacting shoulder.

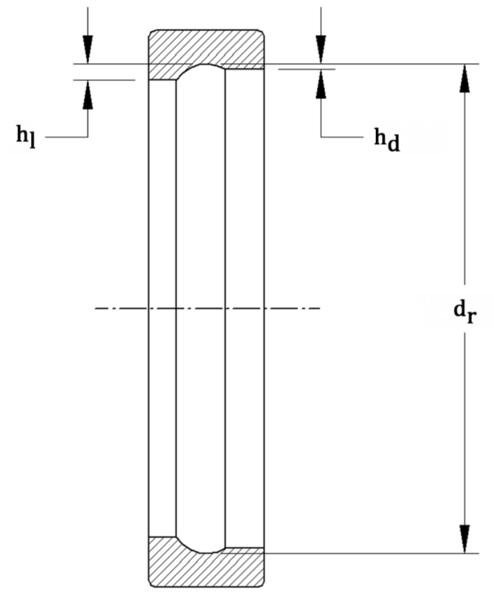
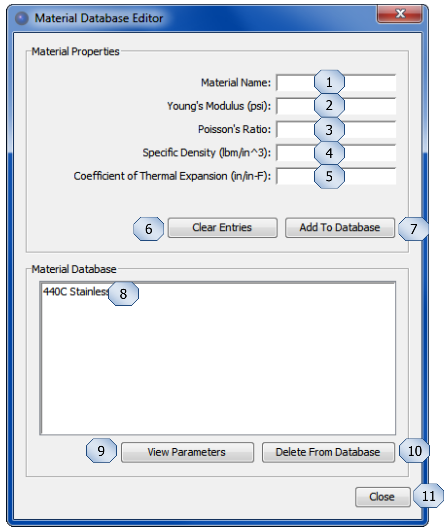


Figure 13. Shoulder Height Definitions for h/d Values

2.2.2 Material Database Editor

The material database editor allows the user to define their own unique materials. Since material definitions are needed for both bearing definitions and shaft/housing definitions it is recommended that the user initially take the time to define all of their most widely used materials before proceeding with analysis setups. If need be, all separate windows within ORBIS, where material assignments are needed for setup, will contain a material editor button that provides direct access to the database editor. See the following figure for a detailed description of the material editor.

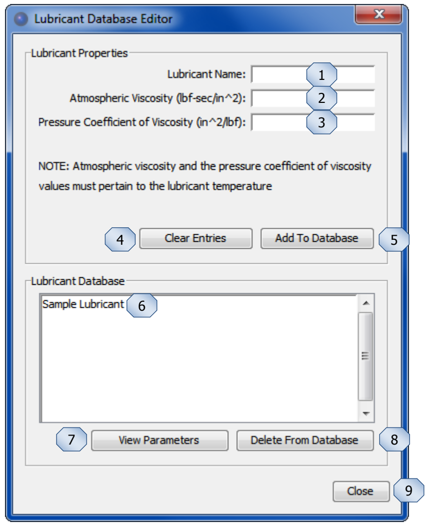


#	Title	Description
1	Material Name	Specify a name for the material.
2	Young's Modulus (psi)	Specifies Young's Modulus for the material.
3	Poisson's Ratio	Specifies Poisson's ratio for the material.
4	Specific Density (lbm/in^3)	Specifies the specific density of the material.
5	Coefficient of Thermal Expansion (in/in-°F)	Specifies the coefficient of thermal expansion for the material.
6	Clear Entries Button	Clears all input entries (does NOT clear the database entries).
7	Add To Database Button	Adds new entire to the Material Database.
8	Material Database Window	Shows the current entries in the Material Database.
9	View Parameters Button	Displays the parameters of a selected material database entry.
10	Delete From Database Button	Deletes the selected database entry from the database.
11	Close Button	Closes the Bearing Database Editor.

Figure 14. Material Database Inputs

2.2.3 Lubricant Database Editor

The lubricant database editor allows the user to define their own unique lubricants. ORBIS currently requires lubricant properties independent of temperature. This means the user must define, and subsequently select, appropriate lubricant definitions that are pertinent to the temperature used in their analysis. See the following figure for a detailed description of the lubricant editor.



#	Title	Description
1	Lubricant Name	Specify a name for the lubricant.
2	Atmospheric Viscosity (lbf-sec/in^2)	Specifies the viscosity of the lubricant.
3	Pressure Coefficient of Viscosity (in^2/lbf)	Specifies the pressure coefficient of viscosity of the lubricant.
4	Clear Entries Button	Clears all input entries (does NOT clear the database entries).
5	Add To Database Button	Adds new entry to the Lubricant Database.
6	Lubricant Database Window	Shows the current entries in the Lubricant Database.
7	View Parameters Button	Displays the parameters of a selected lubricant database entry.
8	Delete From Database Button	Deletes the selected database entry from the database.
9	Close Button	Closes the Lubricant Database Editor.

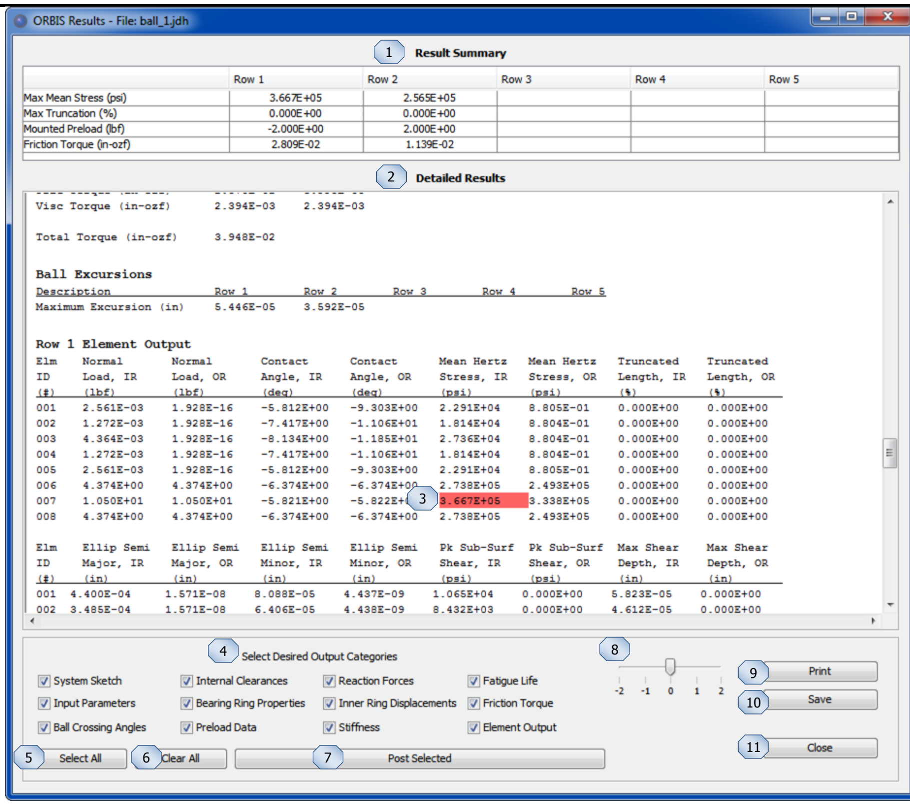
Figure 15. Lubricant Database Inputs

2.3 Analysis Results Window

Professionally formatted analysis output is provided in a standalone window as shown in the following figure. Refer to section 4.0 for a detailed description of all available output. Results are organized to provide quick access and easy interpretation.

All results windows ‘float’, which enables the user to keep the results from an analysis run active; then return to the main window and modify their setup and submit an altered analysis. The user can then compare both analysis results side-by-side.

Typically Result Window is not saved within ORBIS. However, options do exist to save the results to a text file or print them. Since ORBIS generally produces analysis results within a fraction of a second the primary means of saving an analysis is to save the analysis setup from the file menu on the main window. The saved file can then be reopened and all original analysis setup parameters will be restored. To produce the results window the user simply selects the Analyze button to recreate the results window.



#	Title	Description
1	Result Summary	Key result parameters are tabulated for each bearing row. This area provides quick access to available key parameters.
2	Detailed Results	A scrollable/selectable text window containing the complete analysis output. See section 4.0 for a comprehensive listing of available output contained in the detailed results section of the results window.
3	Result Highlighting	Result highlighting makes important result parameters impossible to overlook. Each element Hertzian contact stress exceeding the user specified allowable is highlighted. Additionally, all elements with truncation are automatically highlighted.
4	Output Filter Selection	User can select various categories of output to be displayed in the detailed results selection by selecting the various check boxes.
5	Select All Button	Select this button to have all output categories selected
6	Clear All Button	Select this button to clear all output checkboxes
7	Post Selected Button	Select this button to post all output categories actively selected
8	Adjust Font Size	Font slider adjusts font size, in 1pt increments, for all the detailed results text.
9	Print Button	Brings up a standard print dialog. Only the detailed results are printed.
10	Save Button	Save copies the contents of the results window to a delimited text file. The delimited text file provides the user with unlimited post processing options and easy importing to various software platforms such as Microsoft Excel®.
11	Close Button	Closes the results window.

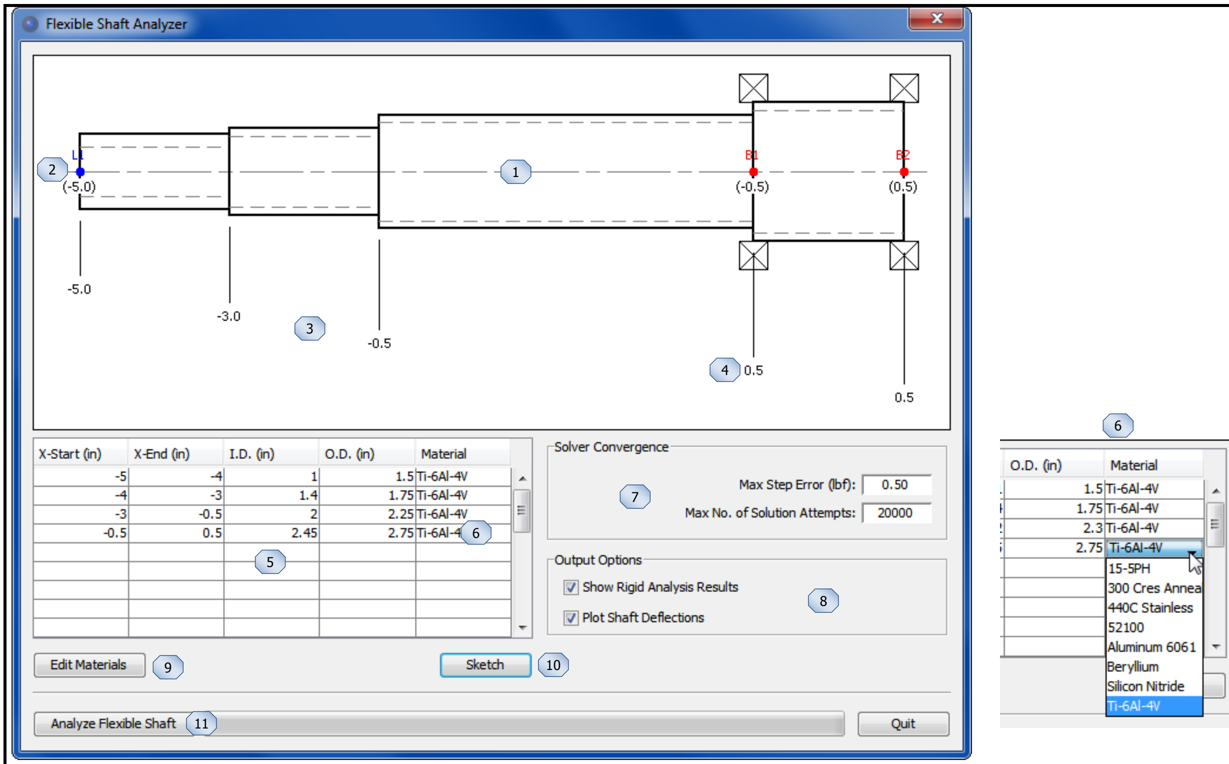
Figure 16. Results Window

2.4 Flexible Shaft Analyzer

The Flexible Shaft Analyzer is used to account for elastic compliance of the bearing shaft. Elasticity model uses Timoshenko beam element formulations that account for both bending and shear deflections in the shaft. The interface allows shaft definition of up to 25 unique circular beam elements; each of which may be defined with unique section dimensions and/or materials. See figure below for descriptions of the flexible shaft window.

To perform an analysis that considers shaft flexibility the user completes their system setup within the main window as if performing a standard rigid analysis. Once the system is setup the user selects the 'Shaft Flexibility' option from the Tools menu to open the Flexible Shaft Analyzer window (as shown in the figure below). Here the user defines their shaft elements, reviews their final setup and submits the final analysis.

If the initially defined rigid system has constant section dimensions, determined by validating all defined bearing I.D.'s and shaft I.D.'s are constant, ORBIS will prepopulate one shaft element within the Flexible Shaft Analyzer window that extends through the complete system. The user may override this assumption by editing the table of shaft elements. For cases where the bearing I.D.'s or shaft I.D.'s are not constant throughout the system no prepopulated elements are provided and the user will need to define shaft elements that extend through all bearing and load locations.



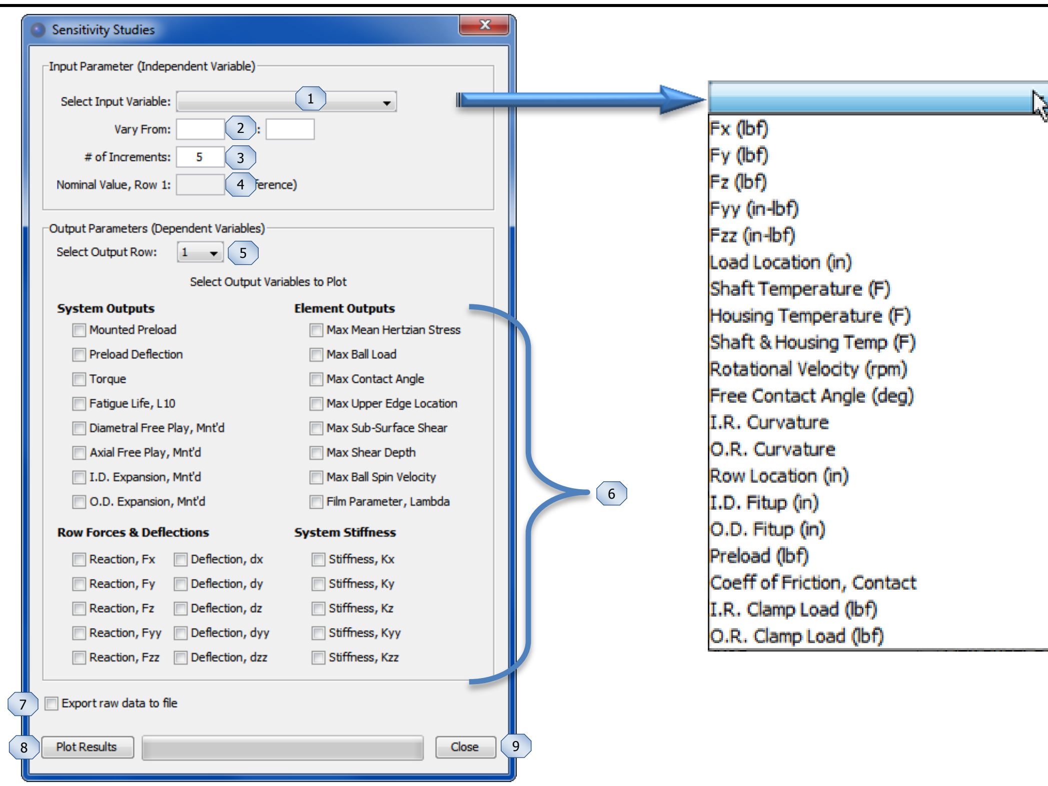
#	Title	Description
1	Shaft Sketch	An engineering sketch is provided for the user defined setup.
2	Load Points	All user defined load points are labeled (L1, L2, etc) with their x-axis coordinate.
3	Element Dimensions	Each user defined shaft element is sketched and dimensioned along the length (x-axis).
4	Bearings	All user defined bearings are sketched and x-axis coordinates are shown.
5	Shaft Element Definition Table	All shaft elements are defined here. All shaft elements are cylindrical and each successive element must start where the previous element ended. Additionally, shaft elements must exist for the entire span of the defined system, consisting of the left-most bearing row or load location to the right-most bearing or load location.
6	Element Material Properties	Unique element properties are assigned in the material column. This column is directly linked to the Material database and materials are easily assigned by selecting from a drop-down menu (as shown on right).
7	Solver Convergence	You can modify the maximum allowable step error and the maximum number of solution attempts. The solver has an adaptive method that continuously reduces the load increment (step size) until either the step error is satisfied or the maximum number of solution attempts has been exceeded.
8	Output Options	Output options exist for showing the rigid shaft analysis results (same results one would get with a normal Orbis analysis from the main window) and whether shaft deflections should be plotted.
9	Edit Materials Button	Launches the Material Database editor.
10	Sketch Button	Once the user has input the shaft element definitions selecting the 'Sketch' button updates the sketch window.
11	Analyze Flexible Shaft Button	Runs the flexible shaft analysis and produces a results window.

Figure 17. Flexible Shaft Window

2.5 Sensitivity Studies

ORBIS enables rapid bearing design and quick solutions to common 'what if' scenarios via the Sensitivity Studies utility. This utility allows the user to vary almost any input parameter (independent parameter) and plot them against any output parameter (dependent parameter). The Sensitivity Study dialog is accessed from the 'Tools' menu (see section 2.1.6) on the main window. This utility requires a complete analysis definition within the main window and also requires the dynamic analysis mode be selected.

The following subsection discusses interaction options for the plot windows generated from all sensitivity study runs. In addition to the generated plots from ORBIS the user can export the raw data used to generate the plots for post processing. The data is saved in a delimited text file that can be easily imported into programs such as Microsoft Excel®.



#	Title	Description
1	Select Input Variable	Drop-down menu to select independent variable (see parameter options in the figure to the right). Note: each input parameter associated with a bearing row is applied to all bearings in the system. For example, if 'Free Contact Angle' is selected as the input parameter all bearing rows will be analyzed with the range of free contact angles defined in entry fields 2 and 3 below.
2	Vary From/To	Specifies the minimum and maximum values, inclusive, to vary the independent variable between.
3	# of Increments	Specifies the number of points to plot. Orbis will use the specified variable limits and number of increments to determine equally spaced data points. Default value is 5 increments.
4	Nominal Value, Row 1	This is a non-editable field that provides the nominal value of the selected independent parameter. This is provided for user reference.
5	Select Output Row	Specifies which output row to be used to plot output (dependent variable).
6	Output Variable Selections	Checkbox selection of all possible output variables. User may select any number of output variables to analyze. Orbis will provide a separate plot window for each output variable.
7	Export raw data to file	Selecting this checkbox will allow the user to save the raw plot data to a delimited text file.
8	Plot Results Button	Button to perform analysis and plot final results. If user selected 'Export raw data to file' checkbox the user will be presented with 'File Save' dialog to specify a file name and directory for the data file prior to plotting the data.
9	Close Button	Closes the Sensitivity Studies dialog.

Figure 18. Sensitivity Studies Dialog

2.5.1 Sensitivity Studies - Plot Windows

The plot windows generated from a sensitivity study are interactive. Separate plot windows are generated for each dependent variable selected in the sensitivity dialog. See the following figure for a description of user options within the plot windows.

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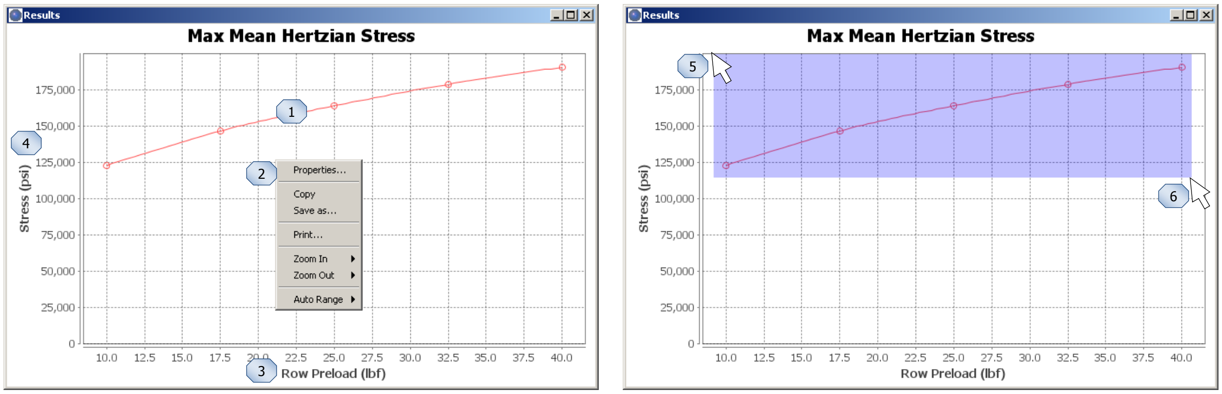
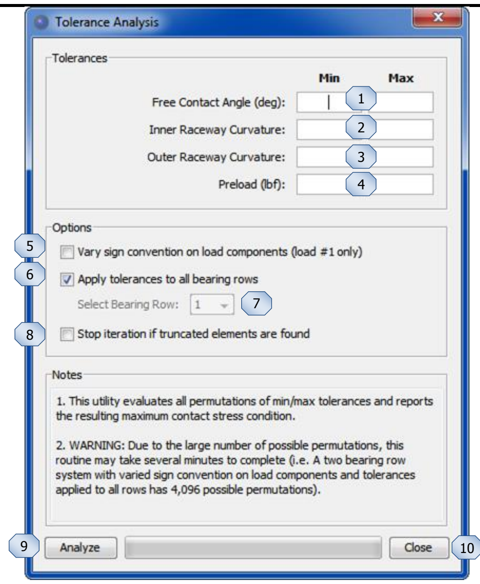


#	Title	Description
1	Curve	Data is plotted with a 'smooth' curve fit where actual solution points are indicated with circles. Note: the smooth curve fit may not always follow data accurately.
2	Plot Options Dialog	The plot options dialog appears by selecting the right mouse button anywhere within the plot window. Options exist to modify plot properties, copy to clipboard, save plot as an image, print, and zoom/scale axes.
3	Independent Parameter	All plots have the independent parameter along the abscissa. Appropriate units will be specified.
4	Dependent Parameter	All plots have the dependent parameter along the ordinate. Appropriate units will be specified.
5	Mouse Zoom - Start	Mouse zooming (rectangular) is achieved by selecting the upper left corner of a rectangle with the left mouse button and dragging the mouse to the lower right hand corner.
6	Mouse Zoom - End	To complete zoom release the left mouse button with the mouse pointer at the desired lower right corner of the zoom rectangle.

Figure 19. Plot Windows

2.6 Tolerance Analysis

ORBIS can perform tolerance studies of key bearing parameters with the Tolerance Analysis dialog. This utility iteratively solves all permutations of user specified tolerances, min and max conditions, and provides the combination causing worst case Hertzian contact stress in a results window. Additionally, the utility can check for truncation and will display a result window with the truncated conditions. Reference the following figure for a description of the Tolerance Studies utility.



#	Title	Description
1	Free Contact Angle (deg)	Specify min and max free contact angles in degrees.
2	Inner Raceway Curvature	Specify min and max inner raceway curvatures (ratio of raceway radius to ball diameter).
3	Outer Raceway Curvature	Specify min and max outer raceway curvatures (ratio of raceway radius to ball diameter).
4	Preload	Specify min and max preload (always as a positive value). Orbis will correct sign based on contact angle orientation and the assumption that the preload should load through the contact angle.
5	Vary Sign Convention	Checkbox to specify if sign convention should be varied on all load components. Selecting this checkbox will run all permutations of positive and negative load components.
6	Apply Tolerances to all rows	Checkbox to specify how tolerances are applied to the system. Selecting this checkbox causes all bearing rows to have specified tolerances analyzed. Un-selecting this checkbox activates item 7 below and tolerances are only applied to selected bearing row.
7	Row Selection Drop-down	When active the drop-down menu is used to specify which bearing row to apply the specified tolerances.
8	Truncation Check	Checkbox to specify if the search algorithm should stop if any element is found to contain truncation. If selected and a set of tolerance conditions results in truncation then the first case found will be shown in a results window.
9	Analyze Button	Button to begin analysis of tolerances.
10	Close Button	Closes the Tolerance Analysis dialog window.

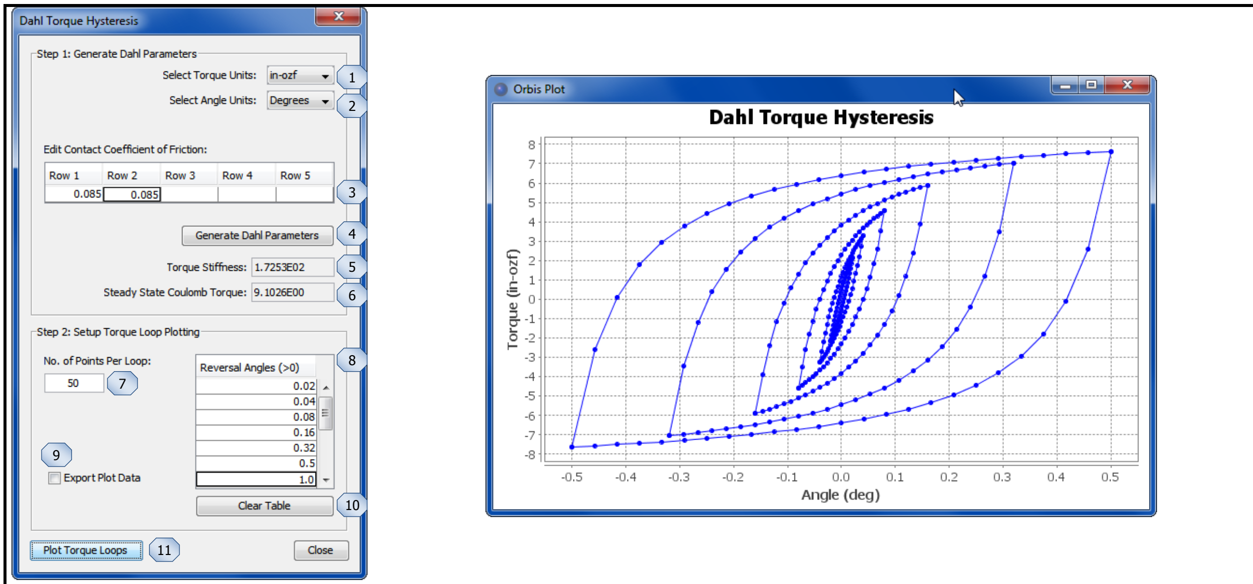
Figure 20. Tolerance Studies Dialog

2.7 Dahl Torque Hysteresis

The Dahl Torque utility is used to analyze the torsional stiffness (torque versus angle) of the bearing system during startup or direction reversal. This phenomenon occurs through small finite angles of rotation, often most apparent when direction of rotation is reversed, at speeds sufficiently slow such that viscous drag is negligible. The utility provides quick inspection of the reversing torque slope and steady state torque. Additionally, the utility can quickly generate small angle hysteresis loops for both graphical plot inspection and data export. The analysis procedures of this utility follow those set forth by Todd and Johnson (1986).

To perform a Dahl torque analysis the user configures their system within the main window as if performing a standard analysis run. Once the system is completely defined the user selects the ‘Dahl

Torque Hysteresis' option from the Tools menu. A new dialog will appear, as shown in the figure below, with various configuration options.

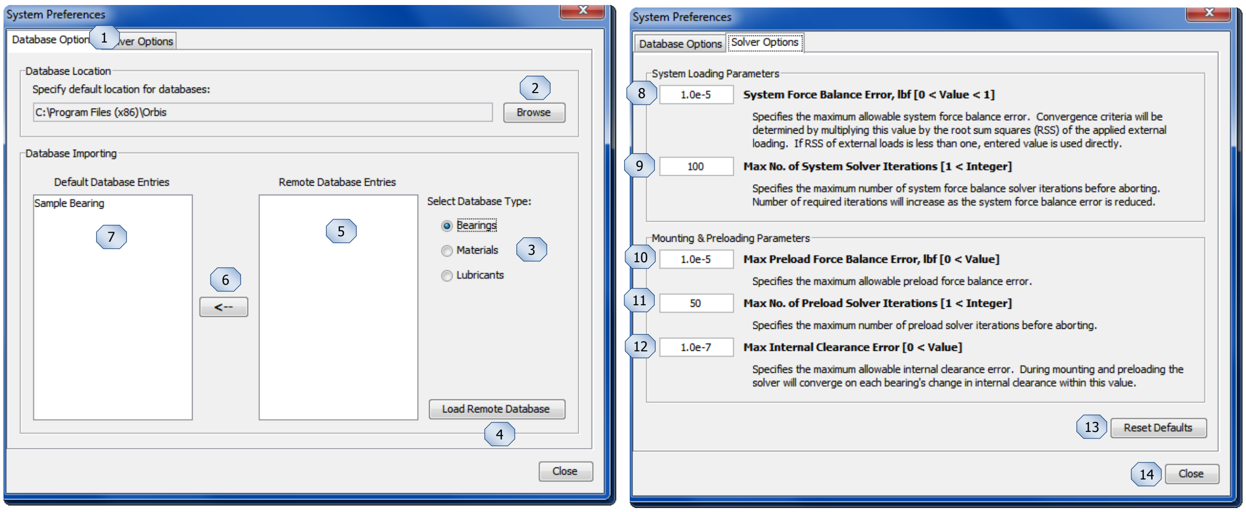


#	Title	Description
1	Torque Units	Drop-down menu allows selection from units of in-ozf, in-lbf, ft-lbf, gm-cm, N-cm or N-m. All subsequent results will be in selected units.
2	Angle Units	Drop-down menu allows selection from units of degrees or radians. All subsequent results will be in selected units.
3	Coefficient of Friction	Tabular input of contact coefficient of friction for each bearing row. Modifications of this parameter will proportionally alter the resulting stead state hysteresis torque.
4	Generate Dahl Parameters Button	Selecting button generates torque stiffness and stead state torque results. See #'s 5 & 6 below.
5	Torque Stiffness	Result has units of torque divided by angle where units are as specified above.
6	Steady State Coulomb Torque	Steady State friction torque value with units as specified above. This can be adjusted by altering the contact coefficients of friction.
7	No. of Points Per Loop	Specifies the number of solution points per hysteresis loop. Points are always equally spaced from +/- reversal angles specified.
8	Reversal Angles	Table allows multiple reversal angles to be generated in the plot output. Units are as specified above. Angles must be entered as positive values greater than zero. A separate loop is generated for each defined table entry.
9	Export Plot Data Checkbox	Selecting this checkbox creates a save dialog once the Plot Torque Loops button is pressed. The user will then be able to save the data from the plot to a delimited text file for post processing.
10	Clear Table Button	Button simply clears all reversal angle data within the table.
11	Plot Torque Loops Button	Clicking this button generates the torque loop plot based on all above user settings. Generated plot window has all standard zoom and right-click context menu options as discussed in Figure 19.

Figure 21. Dahl Torque Hysteresis Utility

2.8 System Preferences

The system preferences dialog is available from the tools menu (reference 2.1.6). These preferences are persistent; meaning they remain in effect each time the user launches and runs ORBIS, until changed from this dialog. Options available are shown in the figure below.



#	Title	Description
1	Tabbed Pane Selection	Each system preference category is accessed by selecting the appropriate tab.
2	Database Location	This area contains the folder location to the default database files. The browse button brings up a folder selection dialog that allows the user to specify their preferred directory for storing their databases.
3	Select Database Type	To perform a database import, or simply view contents of a database, the user must select which type of database to be displayed. Once the type is specified the two scroll panes (see #6 & #7) populate with the appropriate entry names.
4	Load Remote Database	Select this button to bring up a folder selection dialog. Within the folder selection dialog the user will navigate to a desired database. Note: this button is only active once a database type is specified.
5	Remote Database Entries	Displays entries from remote database. Single entry selection is achieved by mouse selection (left click) on desired entry. Multiple entry selection is achieved by two methods: for consecutive entry selection select the first desired entry and shift+click the last consecutive entry, for non-consecutive entry selection select each entry while holding the control key.
6	Import button	Selecting this button imports the selected remote database entries into the default database. The database does not allow duplicate entries and will check each import entry for existing names within the default database. If duplicates are found the user will be asked to confirm overwriting or skip the duplicate import.
7	Default Database Entries	Displays the entries from the user's default database.
8	System Force Balance Error	This entry specifies the allowable system force balance error for solver convergence (Norm of the residuals). Acceptable values are between zero and one exclusive [0<value<1]. The system force balance convergence criteria will be determined by multiplying this value by the RSS of the applied external loading. In the case where the RSS of the external loading is less than one this value will be used directly. For example, if the RSS of the external loading is 1,000 lbf and the system force balance error is 1.0E-5 (default value), then the system will converge to equilibrium within 0.01 lbf.
9	Max Solver Iterations	Specifies the maximum number of numerical solver iterations before aborting.
10	Max Preload Error	This entry specifies the maximum allowable force error for determining the preloaded state. Acceptable values are greater than zero [0<value].
11	Max Preload Iterations	Specifies the maximum number of numerical solver iterations on preload convergence before aborting.
12	Max Internal Clearance Error	Specifies the maximum allowable internal clearance error for convergence, in inches. Acceptable values are greater than zero [0<value]. During mounting and preloading routines the solver will converge on each bearing row's change in internal clearance within this value.
13	Reset Defaults	Select this button to restore all solver options to their default values.
14	Close Button	Closes the system preference dialog window.

Figure 22. System Preferences Dialog

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3.0 Brief Technical Background

ORBIS uses numerical techniques to solve the nonlinear elastic behavior of the user defined system of one or more bearing rows. The model considers each ball-to-race contact for all bearing rows defined in the system; resulting in complete knowledge of the element load distributions and their raceway attitudes. A solution to the system is achieved when the sum of all bearing row reaction forces is sufficiently close to the external applied forces (system equilibrium). Core analysis methods follow the mathematical theories developed and published by A.B. Jones (1964).

The system model essentially follows the logical process necessary to assemble a rotational system: initial conditions are defined, the bearings are fit into the assembly, preload is applied to the bearings, and external loading is finally applied to the mounted and preloaded bearing system. The parameters describing relative axial ring displacements and internal clearance changes are tracked at each step of the process; ultimately leading to the final state of the bearing system.

Since bearings typically operate with very small internal clearances it is important to consider the effects of boundary conditions on the races when establishing the mounted state of the bearing system. ORBIS implements a compliance model based on classical thick ring theories to determine the final mounted and preloaded state of the bearing system. The compliance model is also used for assessing thermal strains. Once all mounting, preloading and thermal strains have been considered the traditional fixed ring theories of are applied to assess effects due to external loading.

The compliance model makes a key assumption that, in the local vicinity of the bearing, the housing, shaft and bearing rings can be expressed with a series of nested rings. Thick ring theory assumes the representative rings have uniform constant wall thickness and all deflections remain within the linear elastic region of the material. Since the groove side of a bearing race clearly has a non-constant cross section an equivalent diameter has been developed (reference section 4.5 for the equivalence model) to represent bearing rings. The equivalence model is shown in section 4.5 and has been correlated to detailed finite element models of standard bearing ring cross-sectional proportions. The compliance model also handles various sudden changes in the boundary conditions of each nested ring, such as when the fit between a bearing O.D. and housing I.D. transitions from clearance to interference due to preload expansion or thermal expansion.

3.1 Preloading

Axial preloading creates radial forces on the bearing rings that increase the bearing's internal clearance—the rings stretch—and change the inner-to-outer ring stickout (axial offset of ring faces when bearing is in is free contact angle position). To find the preloaded state, with account for ring stretch, each bearing row is iteratively solved until the change in internal clearance equals the resultant ring deflection due to preload pressure on the raceways. This algorithm also accounts for nonlinear behavior of axial load versus deflection and potential nonlinear radial ring stiffness due to fitup gap closure.

The preload value entered within each bearings row's preload input (see section 2.1.4) includes options to specify the preload ***condition*** and preload ***type***. These parameters, as discussed below, allow the user to specify at what state the entered preload value is true.

3.1.1 Preload Condition

Since ORBIS treats bearing rings as flexible objects, knowledge of an initial state is needed to determine the final solution. The preload condition radio buttons (reference section 2.1.4) are used specify whether the preload value, as input by the user, applies at the mounted or un-mounted condition.

The term 'mounted' means the bearing has been fit, or mounted, into the shaft/housing system and all boundary influences from interference fitting and ring clamping are included. This means the specified preload will be exactly as input at the mounted state of the bearing. The compliance model will determine what the resulting mounted and preloaded contact angle is and use that as the starting point for any external loading.

Conversely, an un-mounted preload condition means the specified preload value is true when the bearing rings are pressed together axially but are radially unrestrained (free to expand/contract). This is very common for pre-ground matched duplex pairs supplied by most bearing manufacturers. For an un-mounted preload condition it is not necessarily true that the final mounted preload will equal the preload input by the user. This difference will depend on the influence of mounted boundary conditions, such as interference fitting, and the specified ***Preload Type***.

3.1.2 Preload Type

ORBIS handles two different preload types: rigid and spring (reference section 2.1.4). The preload type determines how the preload reacts to mounting and thermal influences.

When the preload type is specified as 'rigid' there is no further axial motion allowed between the rings and their adjacent boundary (shaft or housing). Additionally, when the preload condition is specified as un-mounted, the preload gap determined from radially unrestrained rings will be enforced during the mounting routine. If the mounting fits are tighter than the ring expansions due radially unrestrained preloading then this preload gap enforcement will always result in a mounted preload that is higher than the specified un-mounted value. Perhaps the best way to describe a rigid preload type is when one uses a thick clamp plate, or jam nut, that is torqued down on the bearing with forces much higher than the bearing preload to ensure all pre-ground face gaps have been securely seated.

When the preload type is specified to be 'Spring' then relative motion between the inner or outer rings and their mating shaft or housing is permissible. Once the preload force is overcome the bearing reaction follows the spring rate curve. Spring type preloading essentially bypasses unmounted preload specifications since typical spring rates prohibit noticeable force increase for small deflections—this assumption will be valid for spring rates much lower than the axial stiffness of the bearing, which is often the case.

3.2 Convergence Criteria

ORBIS uses the IEEE 754 technical standards for all floating point arithmetic. All calculations use at least 64-bit precision. Key calculations pertaining to matrix inversion and the overall system Jacobian are extended to 128-bit precision to improve accuracy of the solver. The default criteria for convergence are show below. Refer to section 2.8 for instructions on how to change these settings.

Table 2. Solver Convergence Criteria

Parameter	Default Error (±)	Comments
System Equilibrium Error	0.001%	The allowable system equilibrium error is defined as a percentage of the applied external loading (Euclidean norm of force components). Error is defined as the difference between the norm of all bearing row reaction forces and the norm of the external applied forces. In the case where there is zero external loading the error defaults to 1.0E-5 lbf.
Preload Force Error	1.0E-5 lbf.	Preload force error is defined as the difference between the bearing reaction forces and the applied preload force.
Ring Expansion Error	1.0E-7 in.	The ring expansion error is defined as the difference between ΔP_D input into the Jones model (a 'fixed ring' model) and the resulting ΔP_D due to ring deflections. Ring deflections are determined by using the resulting ball normal forces and associated contact angle to determine an equivalent radial pressure on the bearing ring.

4.0 Output Descriptions

The following sections describe the analysis output generated by ORBIS.

4.1 Input Parameters

This section provides a list of the user inputs used to generate the analysis results. Included are the shaft/housing temperatures and materials, bearing dimensions and materials, row input parameters, and material properties for each material used in the system.

4.2 External Applied Loads

This section displays the user defined system load components and the application point at which they are applied (location is along the x-axis). Loading information for up to three separate load points will be displayed.

4.3 Ball Crossing Angles

Ball Crossing Angles are displayed for each row and are defined as the angular rotation required by a given ring, inner or outer, to cause a ball to travel to an adjacent ball station. These results are based on the mounted bearing contact angle. These angles could be used with the rotational speed to provide characteristic disturbance frequencies for inner or outer raceway defects.

4.4 Internal Clearances

This section provides bearing internal clearances in the diametral (denoted by 'PD') and axial (denoted by 'PE') directions. Note: diametral clearance is also commonly referred to as 'radial play.' Diametral play is defined as the total linear radial distance the inner ring can move relative to the outer ring with negligible applied force. Axial play is defined as the total axial displacement the inner ring can move relative to the outer ring.

Result descriptions for each of the internal clearance outputs are as shown in the following table.

Table 3. Internal Clearance Output Descriptions

Result Title	Parameter Description
Diametral, PD (free)	Radial play of the bearing in its unmounted, or free, state.
Axial, PE (free)	Axial play of the bearing in its unmounted, or free, state.
Delta PD Mount	Change to radial play due to interference and clamping effects (ambient temperature)
Delta PD Preload	Change to radial play due to preloading (ambient temperature)
Delta PD Temp (free)	Change to radial play due to thermal expansions of bearing rings and balls. This is a free bearing condition with applied temperatures.
Delta PD Temp Mount	Change to radial play due to interference and clamping effects at temperature. Fitup at bearing ID and OD are adjusted based on relative thermal expansions. Ring clamping forces are always as input by user and do not get adjusted for temperature.
Delta PD Temp Prld	Change to radial play due to effective preload at temperature. This change represents the difference in radial play from the mounted temperature state to the mounted and preloaded state.
Diametral, PD (tot)	Final effective radial play after all mounting, preloading and temperature effects.
Axial, PE (tot)	Final effective axial play after all mounting, preloading and temperature effects.

4.5 Bearing Ring Properties

This section provides output for the equivalent raceway diameters and the bearing inner and outer diameter expansions due to mounting, preloading and temperate effects. The equivalent raceway diameter is an approximated constant wall representation of the groove side of the bearing ring and is used for the mounting/preloading algorithm (thick-ring theory). The equations for equivalent diameters are defined as function of the bearing geometry as shown in the following figure.

$$\mathcal{D}_{IR} = d_{IR_{race}} + 0.68(h_l + h_d) - \frac{2h_l}{d_{IR_{race}}}(h_l - h_d)$$

$$\mathcal{D}_{OR} = d_{OR_{race}} - 0.68(h_l + h_d) + \frac{2h_l}{d_{OR_{race}}}(h_l - h_d)$$

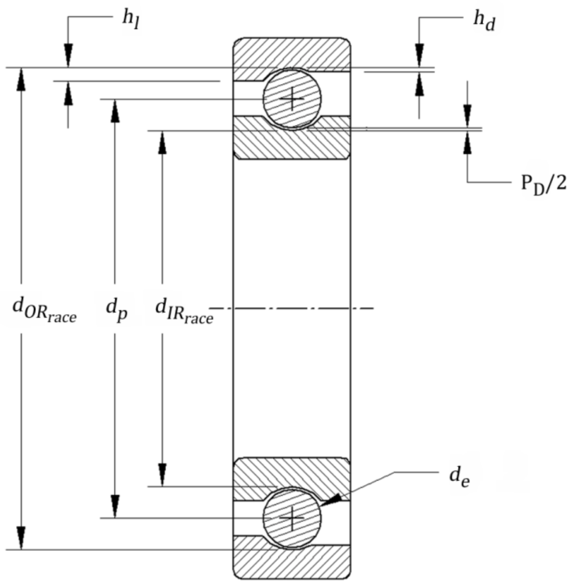

Figure 23. Bearing Nomenclature

The following table provides a detailed description of each of the different bearing ring outputs.

Table 4. Bearing Ring Output Descriptions

Result Title	Parameter Description
I.R. Equiv Diam (in)	Equivalent inner ring diameter as shown in FIG 23 equations
O.R. Equiv Diam (in)	Equivalent outer ring diameter as shown in FIG 23 equations
I.D. Expand, Free (in)	Expansion of bearing inner diameter due to preloading the bearing in a free, radially unrestrained, condition. Applies at ambient temperature.
I.D. Expand, Mnt (in)	Expansion of bearing inner diameter due to ambient mounted and preloaded state. This includes effects from interference fits, ring clamping and preloading.
I.D. Expand, Temp (in)	Expansion of bearing inner diameter due to mounted and preloaded state at temperature. This includes fitup changes due to temperature, ring clamping, and effective preload at temperature.
O.D. Expand, Free (in)	Expansion of bearing outer diameter due to preloading the bearing in a free, radially unrestrained, condition. Applies at ambient temperature.
O.D. Expand, Mnt (in)	Expansion of bearing outer diameter due to ambient mounted and preloaded state. This includes effects from interference fits, ring clamping and preloading.
O.D. Expand, Temp (in)	Expansion of bearing outer diameter due to mounted and preloaded state at temperature. This includes fitup changes due to temperature, ring clamping, and effective preload at temperature.
I.D. Fitup, Mnt (in)	Effective fitup (diametral interference/clearance) between bearing inner diameter and shaft outer diameter at mounted and preloaded state at ambient temperature. This includes fitup changes due to interference, ring clamping, and preloading.
I.D. Fitup, Temp (in)	Effective fitup (diametral interference/clearance) between bearing inner diameter and shaft outer diameter at mounted and preloaded state at temperature. This includes fitup changes due to interference, ring clamping, and preloading.
O.D. Fitup, Mnt (in)	Effective fitup (diametral interference/clearance) between bearing outer diameter and housing inner diameter at mounted and preloaded state at ambient temperature. This includes fitup changes due to interference, ring clamping, and preloading.
O.D. Fitup, Temp (in)	Effective fitup (diametral interference/clearance) between bearing outer diameter and housing inner diameter at mounted and preloaded state at temperature. This includes fitup changes due to interference, ring clamping, and preloading.

4.6 Preload Data

Preload data output shows the applied preload, resulting mounted preload, axial deflections pertaining to mounted preload and the residual preload after temperature effects have been applied. The axial deflection shown is purely due to the mounted preload condition and does not include any temperature effects. To determine additional axial deflections due to temperature loading one could calculate the difference between the Inner Ring Displacement (dx) and the axial deflection in the preload data.

4.7 Reaction Forces on Shaft

This section provides the resulting bearing reaction force components, expressed in global coordinates, on the shaft at each bearing row. These forces include all mounting, preloading and external loading conditions and apply at the center of their respective bearing row locations.

4.8 Inner Ring Displacements

This section provides the total displacement, expressed in global coordinate components, of the inner rings due to mounting, preloading, temperature and external loading. Initial, or zero position, is therefore the unmounted free condition. Note: the axial (dx) displacements due to external loading only can be obtained by taking the difference between the total displacements shown and the axial displacements due to preloading as shown in the Preload Data output section (section 4.6).

4.9 Stiffness Outputs

ORBIS provides three different types of stiffness outputs: axial stiffness with ring compliance considerations, system Jacobian diagonal terms, and complete 5x5 stiffness derivatives for each bearing row. Refer to subsequent sections for a description of each type of stiffness result.

4.9.1 Axial Stiffness with Ring Compliance

This result provides the system axial stiffness, at the mounted and preloaded state, with compliant ring considerations. This output includes the contribution of ring expansion due to an incremental axial load with the traditional bearing contact stiffness to more accurately represent axial stiffness of the mounted and preloaded system. No influences from external loading are included in this stiffness output.

4.9.2 System Jacobian

This result provides the system Jacobian diagonal terms. Results apply in the fully loaded condition. Additionally, the system Jacobian assumes a rigid system during external load application. Results are provided at the system center and each specified load point.

4.9.3 Stiffness at Load Point

When performing a flexible shaft analysis the output contains additional complete stiffness matrices for each load point specified in the system. This matrix represents the full 5 x 5 stiffness matrix of the system at the specified load point. Stiffness results include effects of shaft compliance and bearing stiffness's in their final loaded equilibrium state.

4.9.4 Row Stiffness Matrix

This section provides complete 5x5 stiffness derivatives for each bearing row. Stiffness results correspond to the quasi-static equilibrium state of the system in its final loaded state.

4.10 Fatigue Life

This section provides individual ring and total system fatigue cycles for various conditions. Note: Fatigue results are only generated for dynamic analysis runs. Outputs include L10 life, adjusted L10 life, and adjusted life with consideration for film thickness. L10 Fatigue life calculations are based on the Lundberg – Palmgren theories as shown in Jones (1964). The adjusted life output is based on the life factor theory adopted in AFBMA (1990) standards. This result includes the user defined life factor input along with a computed factor based on the user reliability input.

The life factor input allows the user to enter a combined factor to account for items such as materials, cleanliness, and misalignments. Bamberger (1971) provides a useful reference for computing various life factors. The adjusted life with film includes an additional lubricant factor, which is also provided for reference. The film parameter is from Bamberger (1971) and follows the AFMBA recommended average curve and uses the minimum film parameter as discussed below. All fatigue calculations use the individual rolling element results and do not require determination of an equivalent radial load on the bearing row.

4.11 Bearing Torque

Bearing torque results are only generated for dynamic analysis runs. Two types of torque are considered: friction torque and viscous torque. Friction torque output represents the torque associated with rolling and spinning within the contact area when the balls start rotating. Precisely, this is the torque due to interfacial slip (aka Heathcoate Slip) at the contact ellipse. ORBIS uses the 'Race Control' theory from Jones (1964) and therefore only allows spin to occur on one raceway. The computed torque output can be scaled with the coefficient of friction input parameter. Reference Jones (1964) for the friction torque calculations used by ORBIS.

Viscous torque output is based on the Palmgren model, which was republished by Harris (2001). This model accounts for lubricant viscosity and requires use of a viscous torque factor. Hence, the viscous torque output can be scaled by direct modification of the viscous torque factor.

To achieve optimal torque predictions the user will need to tune both the coefficient of friction at the ball contact and the lubricant viscous torque factor. This is most accurately done by use of existing test data of a known configuration. The coefficient of friction should be tuned first based on breakaway or slow speed test data. The viscous torque factor is then tuned based on test data for two different operational speeds. Note that viscosity is highly sensitive to temperature.

4.12 Ball Excursions

Dynamic runs include output showing the maximum ball excursion for each bearing row. This output represents the maximum circumferential excursion, in units of inches, a ball travels relative to the average ball path. Another way to view this is the maximum amplitude a ball travels within the retainer pocket. This result is achieved by taking the orbital velocities of each ball, determining the average velocity of all balls, integrating the orbital velocities through one full revolution, and finally computing the difference between actual integrated ball positions and the average ball positions. Final reported excursion represents the maximum ball departure from the average.

4.13 Row Outputs (Element-Wise results)

Detailed outputs for each element of each row are provided in tabular form. Output tables are repeated for each bearing row in the user's system. These tables differ depending on whether the analysis is static or dynamic. All outputs correspond to the system equilibrium state after application of all external loading.

4.13.1 Element Number

The Element Number is simply an indexing scheme to identify each of the rolling-elements uniquely. The first ball is always placed along the –Z axis (this is the three o'clock position when looking down the –X axis at the Y-Z plane) and increments in an increasing fashion toward the +Y axis.

4.13.2 Normal Ball Load

The Normal Ball Load is the load applied by each ball into each raceway contact. This load is directly normal to the contact ellipse and has an attitude defined by the contact angle.

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4.13.3 Contact Angle

The Contact Angle output describes the angle of the normal ball load vector to the plane extending through the Y-Z plane.

4.13.4 Mean Hertz Stress

The Mean Hertz Stress output represents the average Hertzian contact stress over the elliptical contact area. Peak stress for an elliptical contact can be computed by multiplying the mean stress by 3/2. ORBIS will automatically highlight, in red, all values that exceed the user defined allowable mean Hertzian stress from the main user interface. All stress results assume the contact ellipse if fully contained within the raceway.

4.13.5 Truncation Analysis

When truncated elements are found additional output is provided directly after the first table of the affected row. This output computes peak center stresses and peak edge stresses for all elements exhibiting truncation. The method used follows the publication by Frantz and Leveille (2001). This output reports peak, not mean, stresses and all edge stresses include a nominal 1.8X edge concentration factor. Since this factor is applied directly to the stress, the user may manually modify edge stresses based on alternate edges stress factors as they see fit.

4.13.6 Truncated Length

The Truncated Length represents the percent of the total length of the contact ellipse, along the major axis, that is truncated due to shoulder or dam override. ORBIS will automatically highlight all elements that have any truncation.

4.13.7 Ellipse Semi Major

The Ellipse Semi Major output represents one half of the major dimension of the contact ellipse.

4.13.8 Ellipse Semi Minor

The Ellipse Semi Minor output represents one half of the minor dimension of the contact ellipse.

4.13.9 Max Sub-Surface Shear

The Max Sub-Surface Shear is the peak shear stress developed below the raceway surface due to contact stress.

4.13.10 Max Shear Depth

The Max Shear Depth is the distance along the normal to the contact area, below the raceway surface, at which maximum shear stress is developed.

4.13.11 Upper Edge Location

The Upper Edge Location represents the edge of the contact ellipse that is closest to the land diameter. This value is represented as a ratio of its height from the center of the raceway to the ball diameter.

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4.13.12 Lower Edge Location

The Lower Edge Location represents the edge of the contact ellipse that is closest to the dam diameter. This value is represented as a ratio of its height from the center of the raceway to the ball diameter.

4.13.13 Contact Normal Approach

Contact Normal Approach represents the total combined deflection of the contacting bodies (rolling-element and raceway). This deflection is along the normal direction to the contact area.

4.13.14 Contact Normal Stiffness

Contact Normal Stiffness represents the stiffness of the rolling-element to raceway contact area stiffness in the normal direction.

4.13.15 Spinning Velocity

Spinning Velocity is the angular velocity of the rolling element about the axis of rotation that is normal to the contact on the un-controlling race. Per Jones' (1964) race control theory, spin can only occur on one raceway while pure rolling occurs on the other. Based on the spinning velocity output one can deduce race control (i.e. if there is zero spinning velocity on a given raceway than that raceway is 'in control').

4.13.16 Rolling Velocity

Rolling Velocity is the relative angular velocity of the rolling element about its own axis of rotation parallel to the contact on the controlling race.

4.13.17 Spinning Torque

Spinning Torque is the component of torque generated by interfacial slip within the contact area due to rolling-element spin.

4.13.18 Rolling Torque

Rolling Torque is the component of torque generated by interfacial slip within the contact area due to pure rolling.

4.13.19 Element Roll Velocity

The Element Roll Velocity represents the rotational velocity of the rolling elements as seen relative to the pitch orbit velocity.

4.13.20 Pitch Orbit Velocity

The Pitch Orbit Velocity is the rotational velocity of the bearing pitch diameter about its spin axis. This is essentially the angular velocity of rolling-element cage or retainer.

4.13.21 Minimum Film Height

The Minimum Film Height represents the thinnest point of the lubricant along the center line of the contact ellipse. This calculation is based on the 'Hard-EHL' theory by Hamrock and Dowson (1981) for fully flooded conditions.

4.13.22 Minimum Lambda Value

Lambda is a dimensionless parameter that is often used to describe the lubricant regime of the bearing. Its value is determined by taking the ratio of the minimum film height to the root sum squares (RSS) of the contacting surface roughness. Mathematically, lambda is defined as follows.

$$\lambda = \frac{h_{min}}{\sqrt{R_{raceway}{}^2 + R_{ball}{}^2}}$$

4.13.23 Centrifugal Force

The Centrifugal Force output represents the radial body force of the rolling element due to its orbital velocity and mass. This force tends to create differing contact angles between the inner and outer race contacts and is treated in the analysis per Jones (1964).

4.13.24 Gyroscopic Moment

The Gyroscopic Moment output represents the spinning body moment of the rolling element due to its angular velocity and inertia. The influences of this force are treated in the analysis per Jones (1964).

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