DSD GUI

User Manual

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1 Introduction

1.1 What is DSD?

DSD is an application used for analyzing drill string statics and dynamics. DSD simulates the interaction of the drill string with the borehole under a variety of steady-state (static) and transient dynamic conditions. DSD can place the drill string in a given borehole, and calculate its equilibrium configuration (deflections, internal forces, and contact forces with the borehole). DSD can also simulate steady-state rotation of the drill string under the constraint conditions of the borehole, and calculate free vibration (natural) frequencies and mode shapes, critical frequencies and the lateral map for eccentric rotation.

DSD can perform a fully nonlinear transient analysis of the dynamics of a drill string rotating in a borehole. Parameters such as the weight on the bit, torque at the top drive, RPM, and properties of friction interactions along the surface of the borehole or bit can be controlled. The transient dynamics can be simulated in stages to analyze complex drilling scenarios. DSD reports results in both graphical form and spreadsheets in order to allow for further post-processing. A variety of outputs can be requested: frequency and mode plots, plots of internal forces, plots of contact forces, deflection curves, WOB and TOB plots, and vibration risk index plots.

1.2 Methods and Software

DSD is based on the finite element method. The drill string is represented by a fully nonlinear finite element model consisting of very accurate corotational beams that allow for arbitrary motions and large rotations. The interaction of the drill string and the borehole is represented by a variety of specialized contact models.

The finite element model is implemented in Matlab. The description of the finite element (FE) calculations and the formulation of geometrically nonlinear 3-D beams are not part of this manual. The mechanics of drill strings interacting with a wellbore under different load conditions were implemented in DSD using the previously mentioned FE methods. This document is the user's manual for the operation of the DSD program.

1.3 Building process and Targets

DSD simulates the various stages in the mechanical deformation of a drill string through a sequence of targets. In this context, the term "target" refers to a well-defined computational result. The target may be a simulation database representing a particular stage (for example, the transient analysis: Rotate) or a visualization of the results of a particular stage (for example, an RPM plot).

The target *T* we are interested in could depend on other targets. Therefore, in order to obtain *T*, DSD calculates only the needed essential intermediate targets to reach the main target *T*. For instance, let us say we are interested in the target "*show_critical_rpm*", and let us assume that we are starting from scratch, i.e. no simulation results exist yet. DSD will then be configured to deliver the target "*show_critical_rpm*", and it will realize that this target depends on the target "*critical_rpm*" which has not been found yet. DSD will then automatically start building "*critical_rpm*, which in turn depends on the target "*setup*". Since this target doesn't exist yet, DSD starts building it, as it does not depend on any other target. Once "*setup*" is built, DSD can then go back to building "*critical_rpm*", which allows it to build the final target "*show_critical_rpm*". This approach allows the DSD program to only build or re-build the targets that are actually needed and that are either missing or are out of date.

The following rules are used to decide whether a target needs to be rebuilt:

- If a target database exists, and its timestamp is newer than the current timestamp in the build context, and if the target data has not changed, then the target is not rebuilt.
- If a target database does not exist, or if the target database exists and its data does not match the target data in the database, then the target needs to be rebuilt. For example, if DSD needs to build the target "*modal*", it will check the target "*selfweight*", which in turn depends on the target "*setup*". Assuming that the target "*setup*" already exists, and that its timestamp is fresher than the timestamp of the target "*selfweight*", DSD then first rebuilds the target "*selfweight*", and only then starts building the target "*modal*".

A similar sequence of events would be triggered if we changed the data of the target "*setup*". After checking for the existence of the target "*selfweight*", DSD looks at "*setup*" and sees that the target data specified for "*setup*" has changed. Therefore "*setup*" will be rebuilt, and consequently "*selfweight*" is also rebuilt, since it depends on "*setup*". Finally, the target "*modal*" can be built.

1.4 How to run DSD from the command prompt

DSD is a compiled application which can be run from the command line. The first argument is the name of the INI file, the second argument is the name of the target to be built. As an example, this line will invoke DSD to build the target "*selfweight*", with the description of the targets available in the file Example_1.ini.

> DSD.exe Example_1.ini selfweight

The executable returns the status of the calculation as either of two values: zero (0) for failure, and one (1) for success. If the last argument (name of the target) is omitted, all targets described in the INI file are built. As an example, the following line will invoke DSD to build the targets "*setup*", "*selfweight*", and "*show_deflection_curve*" whose description was included in the file Example_1.ini.

> DSD.exe Example_1.ini

1.4.1 Logs

DSD writes a log for the performed functions in the working folder. Below is an example of the log file written out in the working folder for a build of the target "*setup*", followed by the build of the target "*show_borehole_profile*".

--- 2013-10-11@14:55:54.342

DSD_build: started for target setup

--- 2013-10-11@14:55:54.345

DSD_build_target: working on setup

--- 2013-10-11@14:56:33.421

DSD_build_target: success for setup

--- 2013-10-11@14:56:33.423

DSD_build: succeeded for setup

--- 2013-10-11@14:56:33.435

DSD_build: started for target show_borehole_profile

--- 2013-10-11@14:56:33.437

DSD_build_target: working on show_borehole_profile

--- 2013-10-11@14:56:33.464

DSD_build_target: working on setup

--- 2013-10-11@14:56:33.633

DSD_build_target: success for setup

--- 2013-10-11@14:56:35.005

DSD_build_target: success for show_borehole_profile

--- 2013-10-11@14:56:35.008

DSD_build: succeeded for show_borehole_profile

DSD also writes a log file in the model folder. This log file has more detailed information, and is specific to the model under consideration. Here is an example of the model log corresponding to the DSD log above:

2013-10-11@14:55:54.42

Model initialized

2013-10-11@14:55:54.423

Reading borehole profile

SurveyListing_sample_model_3.csv

2013-10-11@14:55:54.478

Done

2013-10-11@14:55:54.483

Making drill string

Drill stringModel1.csv

2013-10-11@14:55:54.643

Done

2013-10-11@14:55:54.647

Making wellbore

2013-10-11@14:55:54.805

Done

2013-10-11@14:55:54.809

Making finite element models

2013-10-11@14:55:54.892

Done

2013-10-11@14:55:54.895

Positioning drill string in the wellbore

2013-10-11@14:56:33.296

Done

2013-10-11@14:56:33.698

Showing borehole profile

2013-10-11@14:56:34.203

Done

2013-10-11@14:56:34.208

Saving image

./out\Example_1\borehole_profile.jpg

Here is an example of an INI file with a mistake introduced in its last line: the specification for the measurement units uses an invalid symbol of feet (the correct symbol is ft).

[setup]

model_name = Example_1_w_mistake

bit_distance_from_top = 2000 [ft]

cased_length_fraction = 0

cased_radius = 0.15557+0.007 [m]

drill string_file = Drill stringModel1.csv

input_folder = ./in

output_folder = ./out

survey_listing = SurveyListing_sample_model_3.csv

uncased_radius = 0.15557+0.007 [m]

max_element_length = 90 [feet]

When DSD is run, it fails and returns a value of 0. The log in the working folder can then be inspected. The offending line may also be tracked in the INI file.

--- 2013-10-11@15:46:39.333

DSD_build: started for target setup

--- 2013-10-11@15:46:39.343

DSD_build_target: working on setup

--- 2013-10-11@15:46:39.568

Invalid units specification: feet

--- 2013-10-11@15:46:39.571

DSD_build_target: failure for setup

--- 2013-10-11@15:46:39.573

DSD_build: failed for setup

---

2 DSD GUI Interface

The DSD graphical user interface (GUI) provides a means for the user to run DSD, generate, and execute INI files. The features in the Main Window are numbered according to their order of use as shown in Figure 1. The sequential instructions for running a simulation are also presented below.

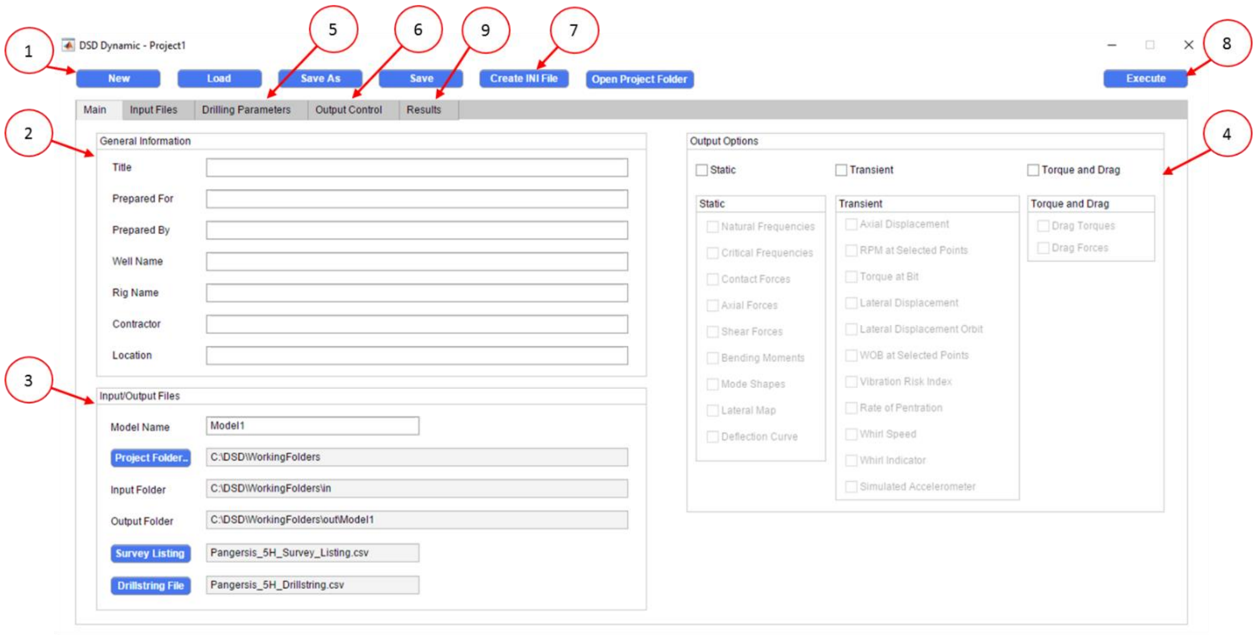


Figure 1 – DSD Main Window

1. **Initialize the simulation using 'New', 'Load', 'Save' and 'Save As'**

   The 'New' button clears all entries and restores default values.

   The 'Load' button loads all GUI settings and inputs previously saved to a '.mat' file.

   The 'Save As' button allows you to browse to a directory to save all current GUI settings and data to a '.mat' file.

   The 'Save' button overwrites all current GUI settings and data to the currently opened/previously saved '.mat' file. In this case, the file 'Project1.mat' will be overwritten by the parameters specified in the GUI.

   The 'Open Project Folder' button opens the current Project Folder. In this case, the directory path is set to 'C:\DSD\WorkingFolders'.

2. **General Information Panel**

   The General Information Panel allows the user to save simulation details for future sessions.

3. **Input/Output Files Panel**

   The input and output folder paths are set by browsing for the 'Project Folder' and entering a 'Model Name'. The 'Project Folder' contains two folders, 'in' and 'out', corresponding to the location of the input and output files respectively.

The user should copy the Survey Listing and Drillstring Files to the ‘Input Folder’ path that is shown. The ‘Output Folder’ will be created in the ‘out’ folder and is labelled using the ‘Model Name’ as shown.

The ‘Survey Listing’ file contains information about the length and orientation of the borehole profile. The ‘Drill string’ file contains information about the drill string composition. See the Input Files section for further details.

Once loaded, the contents of both files will be displayed in the ‘Input Files’ tab.

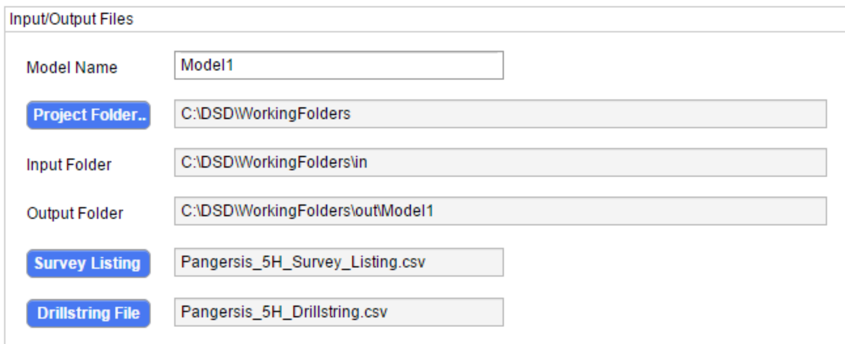


Figure 2 - Input/Output Files Panel

4. Output Options Panel

The Output Options panel allows the user to select the required simulation type in each category: Static, Transient or Torque and Drag. Once selected, the user should navigate to the Drilling Parameters and Output Control tabs to fill in the required panels.

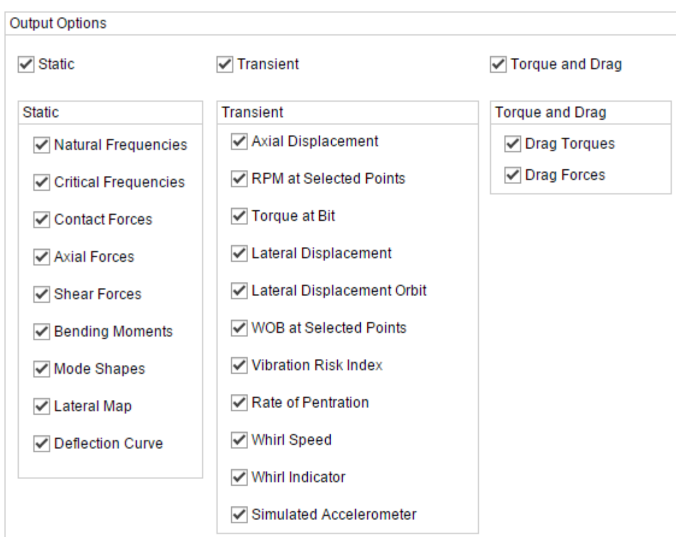


Figure 3 - Output Options Panel

5. Drilling Parameters Tab

The drilling parameters tab contains numerous panels for each simulation type. It allows the user to set simulation parameters that are required by each simulation target.

6. Output Control Tab

The output control tab contains options to control how the results will be visualized for each visualization target.

7. Create INI File Button

Once all parameters have been entered, this button allows the user to generate the INI file in the project folder. This file can be used to run DSD from the command prompt if required, allowing the user to run simulation batches.

8. Execute Button

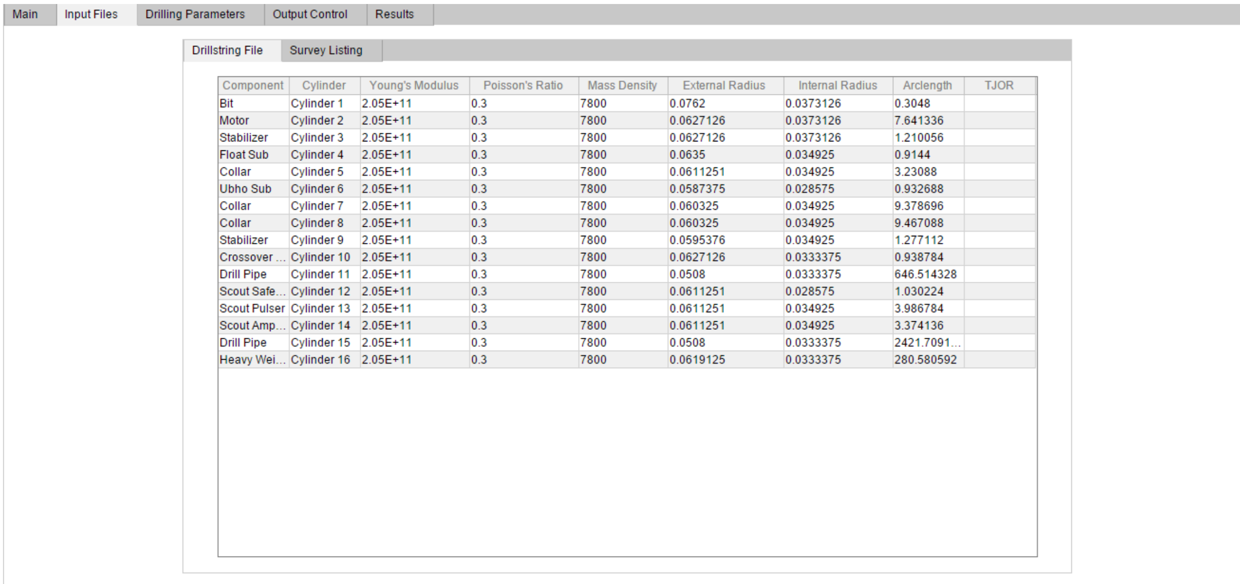
The simulation can be executed and tracked from the GUI. If files are present from a previous run in the output folder, these will be checked for their use in the current simulation. These files may be overwritten, and so the user can change the Model Name if they desire the output to be placed in a different folder. The image names in the Output Control tab for each visualization target can also be changed instead.

9. Results Tab

The resultant images are displayed in the Result Tab. Any spreadsheet output of the data is located in the output folder.

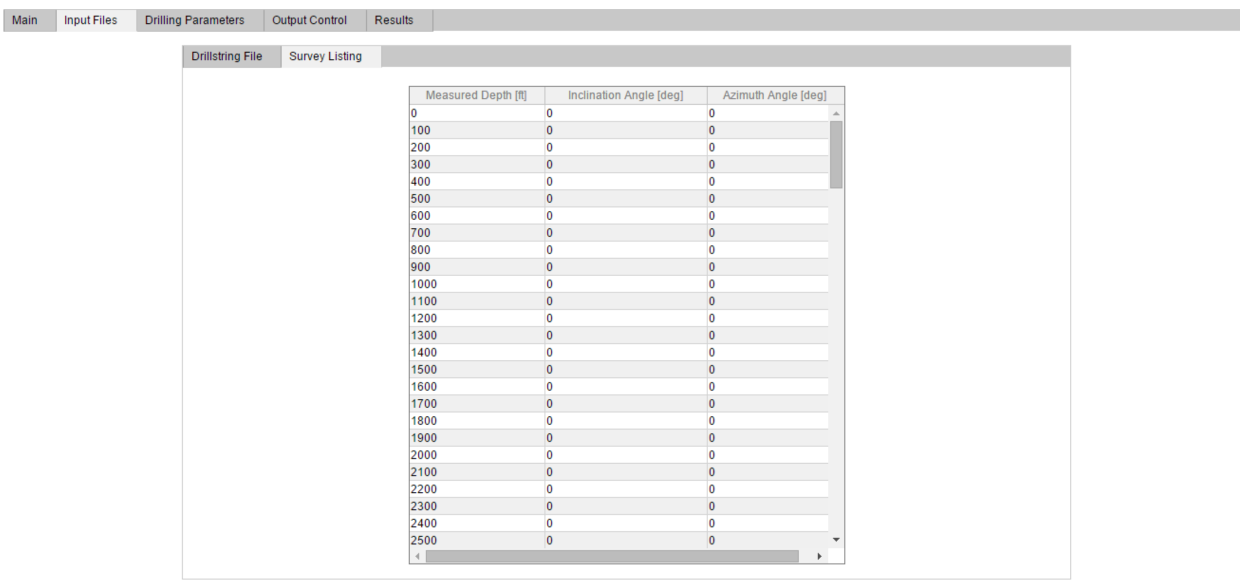
3 Input Files

The ‘Drill string’ and ‘Survey Listing’ files are displayed in the ‘Input Files’ tab once they are loaded, as shown in Figure 4 and Figure 5. The following sub-sections give further details on the allowed input types.



Component	Cylinder	Young's Modulus	Poisson's Ratio	Mass Density	External Radius	Internal Radius	Arclength	TJOR
Bit	Cylinder 1	2.05E+11	0.3	7800	0.0762	0.0373126	0.3048	
Motor	Cylinder 2	2.05E+11	0.3	7800	0.0627126	0.0373126	7.641336	
Stabilizer	Cylinder 3	2.05E+11	0.3	7800	0.0627126	0.0373126	1.210056	
Float Sub	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.034925	0.9144	
Collar	Cylinder 5	2.05E+11	0.3	7800	0.0611251	0.034925	3.23088	
Ubho Sub	Cylinder 6	2.05E+11	0.3	7800	0.0587375	0.028575	0.932688	
Collar	Cylinder 7	2.05E+11	0.3	7800	0.060325	0.034925	9.378696	
Collar	Cylinder 8	2.05E+11	0.3	7800	0.060325	0.034925	9.467088	
Stabilizer	Cylinder 9	2.05E+11	0.3	7800	0.0595376	0.034925	1.277112	
Crossover ...	Cylinder 10	2.05E+11	0.3	7800	0.0627126	0.0333375	0.938784	
Drill Pipe	Cylinder 11	2.05E+11	0.3	7800	0.0508	0.0333375	646.514328	
Scout Safe...	Cylinder 12	2.05E+11	0.3	7800	0.0611251	0.028575	1.030224	
Scout Pulser	Cylinder 13	2.05E+11	0.3	7800	0.0611251	0.034925	3.986784	
Scout Amp...	Cylinder 14	2.05E+11	0.3	7800	0.0611251	0.034925	3.374136	
Drill Pipe	Cylinder 15	2.05E+11	0.3	7800	0.0508	0.0333375	2421.7091...	
Heavy Wei...	Cylinder 16	2.05E+11	0.3	7800	0.0619125	0.0333375	280.580592	

Figure 4 - Drill string File Display



Measured Depth [ft]	Inclination Angle [deg]	Azimuth Angle [deg]
0	0	0
100	0	0
200	0	0
300	0	0
400	0	0
500	0	0
600	0	0
700	0	0
800	0	0
900	0	0
1000	0	0
1100	0	0
1200	0	0
1300	0	0
1400	0	0
1500	0	0
1600	0	0
1700	0	0
1800	0	0
1900	0	0
2000	0	0
2100	0	0
2200	0	0
2300	0	0
2400	0	0
2500	0	0

Figure 5 - Survey Listing Display

3.1 Survey Listing

The Borehole profile file is a 3-column, comma-delimited text file which specifies the length and orientation of the borehole. Survey listings can be in one for three formats; Cartesian, Polar or single-point survey. Both the format and the units are automatically detected. Units of length can either be in feet (specified by the abbreviation ft) or meters (specified by the abbreviation m). The units of the angular measure are assumed to be in degrees. A description of each of the file formats are given below.

1. **Cartesian.**

   In this format, the three columns represent True Vertical Depth (TVD), N(+)/S and E(+)/W. The TVD corresponds to the negative z-axis, the N(+)/S to the +y/-y axis and the E(+)/W to the +x/-x. An example of a file in Cartesian format is shown below.

   TVD,N(+)/S,E(+)/W

   ft,ft,ft

   0.00,0.00,0.00

   0.00,2788.71,0.00

   8.20,2962.55,0.00

2. **Polar**

   In this format, the three columns represent the Measured Depth (MD), Inclination and Azimuth. Inclination is defined as the angle that the borehole makes with the vertical. Therefore, a 0 degree inclination is vertical (downward pointing) and a 90 degree inclination is horizontal in direction. An angle greater than 90 degrees refers to “drilling up”. Azimuth is defined as having a value of 0 degrees for a North heading, 90 degrees for an East heading, 180 degrees for a South heading, and 270 degrees for a West heading. An example of a file in polar format is shown below.

   MD,INC,AZ

   ft,deg,deg

   0.00,0.00,0.00

   266,0.14,187.83

   327,0.31,257.33

3. **Single-point survey**

   This is a condensed version of the survey file and consists of one line with five entries. The first three entries specify the location of the bit using measured depth, inclination and azimuth. The next two entries specify constant build and walk rates between the between the bit and the top of the BHA. The wellbore profile along the length of the BHA is calculated by DSD. A sample entry is shown below.

   MD,INC,AZ,Build Rate,Walk Rate

   ft,deg,deg,deg/100 ft,deg/100 ft

   16500,19.9,202.42,0.1,-0.76

3.2 Drillstring File

The drill string file is a Comma-Separated Value (CSV) spreadsheet that describes the drill string composition. All dimensions (radii and arc lengths) are assumed to be in meters. The mass density is assumed to be in kilograms per meter cubed. The Young's (elasticity) modulus is assumed to be in Pascals. Figure 6 shows an example of a 10-component drill string, where each component consists of a single cylinder. Note that an optional outer radius of the tool joints is specified.

Component	Cylinder	Youngs	Poisson	Mass Dens	Eff External Radius	Eff Internal Radius	Arclength	TJOR
Tri-Cone Bit	Cylinder 1	2.05E+11	0.3	7800	0.108	0	0.3	
Drill Collar	Cylinder 2	2.05E+11	0.3	7800	0.07	0.029070552	40	
Heavy Weight	Cylinder 3	2.05E+11	0.3	7800	0.0635	0.031500622	150	0.08255
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	200	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	200	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	200	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	400	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	1000	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	1000	0.0889
Drill Pipe	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.051315772	809.7	0.0889

Figure 6 – 10 Component Drill string Input File

The abbreviations in the first line of the file are as follows: Comp.= component, Cyl.= cylinder, Youngs= Young's modulus, Poiss.= Poisson ratio, Mass D.= mass density, Eff. Ext. Rad.= effective external radius, Eff. Int. Rad.= effective internal radius, Arclength= arc length, and TJOR = tool joint outer radius.

Note that the value TJOR (the tool joint outer radius) is optional. If it is not supplied, the effective external radius is considered instead of the tool joint radius. The radius is used in any calculation that involves contact with the borehole surface. Using the correct radius is crucial especially in calculations of the frictional torques. If the tool joint radius is known (and different from the effective external radius), it should be supplied as an input. Figure 7 shows an example of an 8-component drill string, where each component consists of one or more cylinder. Note that the elastic properties may be specified for each cylinder or for each component.

Component	Cylinder	Youngs	Poisson	Mass Density	Eff External Radius	Eff Internal Radius	Arclength
Component 1	Cylinder 1	2.05E+11	0.3	7850	0.13018	0	0.0508
	Cylinder 2				0.15557	0	0.2794
	Cylinder 3				0.10477	0	0.127
Component 2	Cylinder 4	2.05E+11	0.3	7850	0.10477	0.0381	0.1524
	Cylinder 5				0.15557	0.0381	0.6096
	Cylinder 6				0.10477	0.0381	0.1524
Component 3	Cylinder 7	2.05E+11	0.3	7850	0.10477	0.0381	1.524
Component 4	Cylinder 8	2.05E+11	0.3	7850	0.10477	0.066421	8.5344
Component 5	Cylinder 9	2.05E+11	0.3	7850	0.10477	0.03937	0.3048
	Cylinder 10				0.15319	0.03937	1.2192
	Cylinder 11				0.10477	0.03937	0.3048
Component 6	Cylinder 12	2.05E+11	0.3	7850	0.10477	0.065659	6.7056
Component 7	Cylinder 13	2.05E+11	0.3	7850	0.10477	0.0381	0.6096
Component 8	Cylinder 14	2.05E+11	0.3	7850	0.10351	0.03556	0.6096
	Cylinder 15				0.15557	0.03556	1.8288
	Cylinder 16				0.10351	0.03556	0.6096

Figure 7 – 8 Component Drill string Input File

4 Drilling Parameters

4.1 General

4.1.1 Setup

The setup panel is required for all simulation types and is the first target built in any simulation. This target establishes the initial static equilibrium of the drill string once it is inserted into the borehole.

The model is first initialized.

The model is initialized with basic quantities such as: system of measurement units, input and output folders. The input folder must exist and be accessible. If the output folder does not exist, it will be created. The borehole profile is read and initialized. The list of control points is refined internally to maintain the shape of the curve. The transitions between segments are first refined with tangency-enforcing points, and the segments of strong curvature then have additional points inserted.

The drill string is read and initialized.

The drill string is localized by placing the bit at the indicated distance from the surface (measured depth). Note that the length of the borehole profile must be longer than the total length of the drill string.

The wellbore data structure is created.

The finite element method machine (FEMM) data structures are created. The FEMMs represent the mechanical response of the drill string and the interaction of the drill string and the wellbore. The model of the drill string is positioned in the borehole.

The drill string finite element model is positioned within the confines of the borehole surface by nonlinear iterations of equilibrium. This means that the drill string is placed in equilibrium inside an arbitrarily curved borehole. The bending of the drill string and the contact of the drill string with the borehole surface are correctly represented. In general, the drill string is not going to be stress-free in a curved borehole, and the contact forces between the drill string and the borehole are not going to be zero.

A description of the parameters needed in the setup panel, shown in Figure 8, is now presented.

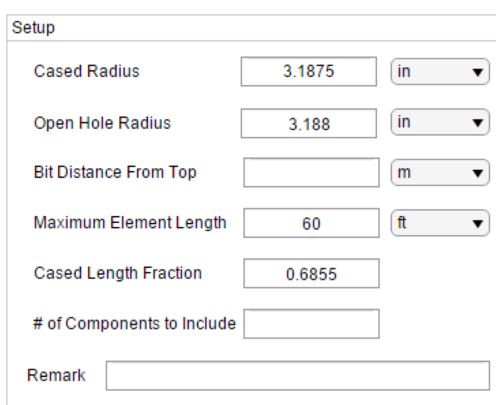


Figure 8 - Setup Panel

Cased Radius	Radius of the cased part of the borehole. If the cased_length_fraction is supplied as greater than zero (i.e. if part of the whole is actually cased), the cased_radius parameter must be supplied.
Open Hole Radius	Radius of the open (uncased) hole. The uncased_radius parameter must always be supplied.
Bit Distance From Top	The bit distance from top (i.e. the measured depth of the bit) can be supplied as empty ([]), in which case the top of the drill string will be at the surface.
Maximum Element Length	Maximum allowed length of a finite element in the mesh of the drill string tubulars. Except for greatly curved boreholes, the default length should be acceptable for good accuracy. The user may verify the accuracy of the simulations by reducing this parameter, rerunning the simulations, and comparing the results. Alternatively, this convergence behavior may be studied by increasing max_element_length by some factor and comparing the results for the two different element lengths.
Cased Length Fraction	Fraction of the length of the borehole that is cased, non-dimensional. The value must be between zero and one, inclusive.
# of Components to Include	Number of components to include in the model of the drill string from the file. If supplied as empty ([]), taking all components specified in the file to be part of the drill string is implied. Otherwise, components 1 (the bit), 2, ..., up to the specified number are taken from the drill string file and included in the drill string simulation.
Remark	A one line comment to describe the target (optional).

4.1.2 Self Weight

This target establishes static equilibrium of the drill string under self-weight and drilling loads.

Equilibrium

The equilibrium of the drill string is obtained by dynamic relaxation. The drill string is allowed to deform dynamically and the kinetic energy is filtered out by numerical dissipation of the Newmark time integration algorithm and by ad hoc mass-and stiffness-proportional Rayleigh damping. The nonlinear incremental problem in each time step is solved by iteration. In addition, the hook force is updated at selected time instants in order to obtain the desired weight on bit. The hook force is calculated with the following tolerance:

$$Hook\_force\_tol = max([1e\text{-}3 \times WOB, 1e\text{-}5 \times Initial\_guess\_of\_Hook\_force])$$

Here WOB is the weight on bit, and Initial_guess_of_Hook_force is the initial estimate of the hook force. The contact with the borehole is in this computation is considered to be frictionless.

Boundary conditions

The boundary conditions are as follows: At the top drive we apply spring restraints against lateral displacements, effectively enforcing a pinned condition at the rotary table, and all rotations are also penalized by spring constants. At the bit we apply an axial restraint in order to mimic rock-bit contact. Finally, at the top drive a hook force is applied in the direction tangential to the borehole curve, with a magnitude that will produce the weight on bit (WOB) as given in the target data. Since the hook force to produce the desired WOB is unknown in general, we need to calculate it iteratively from the condition of equilibrium.

Fluid Mass Density	Mass density of the drilling fluid.
Weight On Bit	Weight-on-bit (WOB) force.
Remark	A one line comment to describe the target (optional).

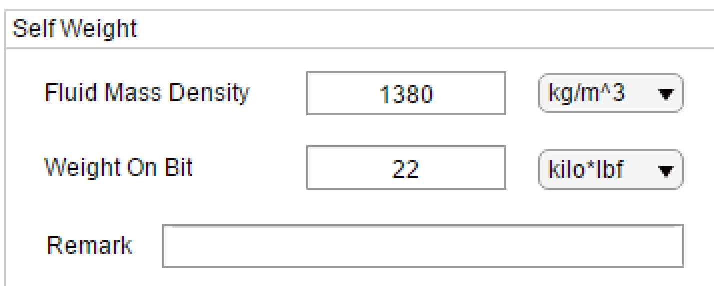


Figure 9 - Self Weight Panel

4.2 Static

4.2.1 Modal

This target sets up the boundary conditions for subsequent modal analyses.

The contact with the borehole is evaluated in order to find the location of the temporary supports for the modal analysis. The drill string is assumed to be in contact with the borehole when the contact force is greater than some minimum value. This minimum contact force is a fraction of the axial stiffness of the drill string multiplied by the ratio of the borehole radius to the length of the drill string. Lateral displacement constraints are added at all points with significant contact force and at the top and bottom of the drill string. Axial rotation is prevented at the rotary table and also at the bit.

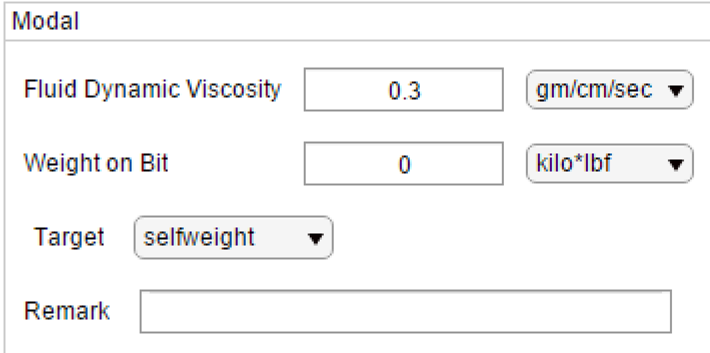


Figure 10 - Modal Panel

Fluid Dynamic Viscosity	Dynamic viscosity of the drilling fluid.
Remark	A one line comment to describe the target (optional).
Weight On Bit	Weight-on-bit (WOB) force.
Target	Target onto which modal analysis is applied.

4.2.2 Free Vibration

This target solves the free-vibration problem for the drill string under static loads and borehole constraint. It is important to note that one must be careful not to ask for too many natural frequencies, since the total number of frequencies is equal to six times the number of the finite elements in the model. The forces that maintain the static equilibrium of the drill string (pre-stress) are taken into account. For instance, axial tension in the string would tend to raise the natural frequencies, while axial compression would decrease them.

Boundary conditions

The boundary conditions are as described for this target below.

Number of Modes	Number of free-vibration modes (natural frequencies) that should be solved for.
Remark	A one line comment to describe the target (optional).

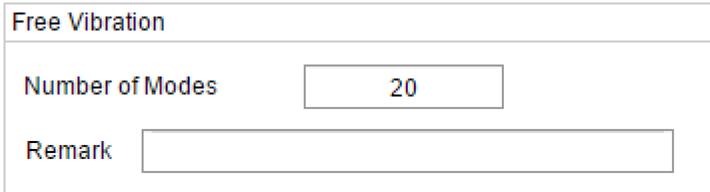


Figure 11 - Free Vibration Panel

4.2.3 Critical RPM

This target solves the critical-rpm problem for a drill string rotating at steady-state with lateral eccentricity, under static loads and borehole constraints. The steady-state harmonic vibration problem is solved for the drill string rotating with an eccentric axis. Static drilling loads and pre-stress due to self-weight and drilling loads are considered. Damping and gyroscopic forces are also included.

Boundary conditions

The boundary conditions are as described for this target below.

RPM Start	RPM range start.
RPM Step	Step to sample the rpm range.
RPM Stop	RPM range stop.
Eccentricity	Eccentricity of the axis about which the drill string rotates.
Torque On Bit	Applied torque on bit.
Weight On Bit	Applied weight on bit.
Remark	A one line comment to describe the target (optional).

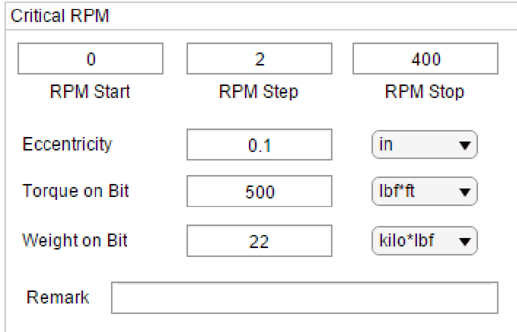


Figure 12 - Critical RPM Panel

4.2.4 Lateral Map

This target solves the critical-rpm problem for the drill string rotating at steady state with lateral eccentricity under the borehole constraint and a range of static loads. The steady-state harmonic vibration problem is solved for the drill string rotating with an eccentric axis. Static drilling loads and pre-stress due to self-weight and drilling loads are considered. Damping and gyroscopic forces are included.

Boundary conditions

The boundary conditions are as described for this target below.

WOB Start	Starting WOB for range of the applied weight on bit.
WOB Step	Step to sample the weight on bit range.
WOB Stop	Stopping WOB for range of the applied weight on bit.
RPM Start	RPM range start.
RPM Step	Step to sample the rpm range.
RPM Stop	RPM range stop.
Eccentricity	Eccentricity of the axis about which the drill string rotates.
Torque On Bit	Applied torque on bit.

Remark	A one line comment to describe the target (optional).

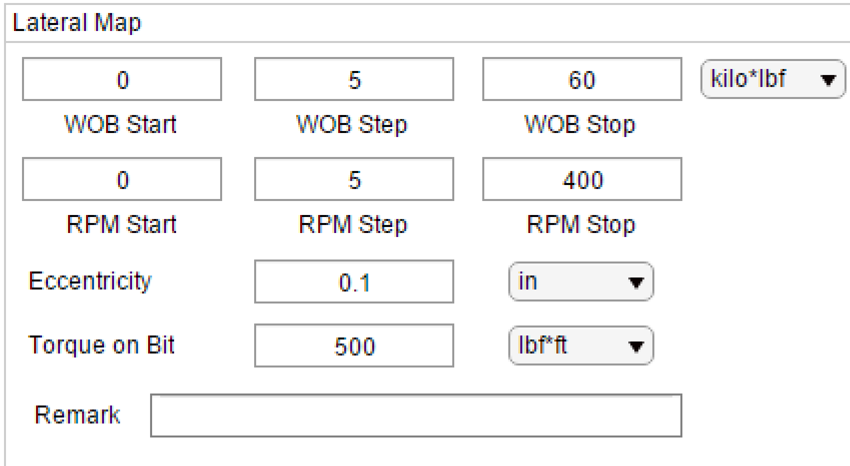


Figure 13 - Lateral Map Panel

4.3 Transient

4.3.1 General

This target computes the fully-nonlinear time-dependent response of a rotating drill string.

Boundary conditions

The boundary conditions are as follows: At the top drive spring restraints against lateral displacements are applied and the rotations, except for the axial one, are also penalized by spring constants. At the bit, a unilateral axial restraint is applied to mimic rock-bit contact. Finally, a hook force is applied at the top drive in the direction tangential to the borehole curve of a magnitude that will produce the weight on bit (WOB) as given in the target data. The top drive (hook) force is obtained from its static value (calculated for the selfweight target) and the static value of the WOB. Therefore for a given value of the dynamic WOB, the corresponding hook force is calculated as:

$$HookForce(t) = -WOB(t) + Static\_Hook\_force + Static\_WOB.$$

Time stepping

The equilibrium of the drill string is obtained by dynamic time-stepping with adaptive time step selection. The convergence is monitored both in the magnitude of out-of-balance forces and in the magnitude of the iterative correction to the displacements. When convergence cannot be achieved with the current time step, the time step is reduced and the iteration is re-tried. Conversely, if the iteration was brief and successful, an attempt is made to increase the time step length, up to the limit that is set by the minimum number of time steps per revolution.

Maximum Sliding Velocity	Sliding velocity along the surface of the wall for which the friction has a maximum. The DSD model of dynamic friction uses a regularized description of the coefficient of dynamic friction. The equation for the coefficient of frictional force represents a transition between static friction (for very small sliding velocity) and dynamic friction (for relatively large sliding velocity). The normally discontinuous relationship between angular velocity and coefficient of friction is approximated with a hyperbolic-tangent function. The relationship between the friction coefficient magnitude and the sliding velocity attains a maximum for very small relative velocities of the component in contact with the borehole wall. This coefficient applies to both axial and circumferential sliding.
Maximum Angular Sliding Velocity	Rotating velocity at the bit for which the dynamic friction has a maximum. The DSD model of dynamic friction uses a regularized description of the coefficient of dynamic friction. The equation for the coefficient of frictional torque represents a transition between static friction (for very small angular velocity) and dynamic friction (for relatively large angular velocity). The normally discontinuous relationship between angular velocity and coefficient of friction is approximated with a hyperbolic-tangent function. The relationship between the friction coefficient magnitude and the rotating velocity attains a maximum for very small angular velocities. This coefficient applies to the dynamic friction at the bit.
Initial RPM	RPM at the start of the drilling operation.
Maximum RPM	Estimate of the fastest rpm at which the drill string is going to rotate. This parameter is not constrained by the actual motion of the bit, only the maximum allowable time step.
Minimum Steps Per Revolution	The smallest number of steps per revolution of the bit. This, in conjunction with Maximum RPM determines the maximum time step that the integrator is allowed to take.
WOB Table	Array of corresponding WOB values. The current WOB is obtained by interpolating from the tables of times and WOB values.
Times	Array of times at which WOB values are given.
Modal Damping	Amount of Rayleigh modal damping. This is a non-dimensional fraction, generally much less than 1.0. It is used to model structural damping in the drill string. There is considerable uncertainty as to how much structural damping should be included, and the default value is an estimate generally used for steel structures.
Modal Damping Frequencies	Frequencies for which Rayleigh modal damping should be applied. The coefficients of the Rayleigh damping are fitted to two frequencies. These are generally rather low frequencies given the considerable flexibility of the drill string in torsion.
Restart From Number	Specifying 0 means start from scratch; while a positive integer specifies the number from which to resume the computation.

Save As Restart Number	Save the computed data as this restart number; if this is supplied as less than zero, it is assumed that 'Save As Restart Number' = 'Restart From Number'+1.
Simulation Start Time	Time at which the direct time stepping starts.
Simulation Stop Time	Time at which the direct time stepping ends.
Bottom Hole Profile Amplitude	Amplitude of the bottom unevenness, which can generate oscillation in the WOB, with the angular frequency given by the parameter Bottom Hole Angular Frequency.
Bottom Hole Angular Frequency	Angular frequency of the bottom unevenness. For the tri-cone bit this will be $3 \times 2\pi$.
Remark	A one line comment to describe the target (optional).

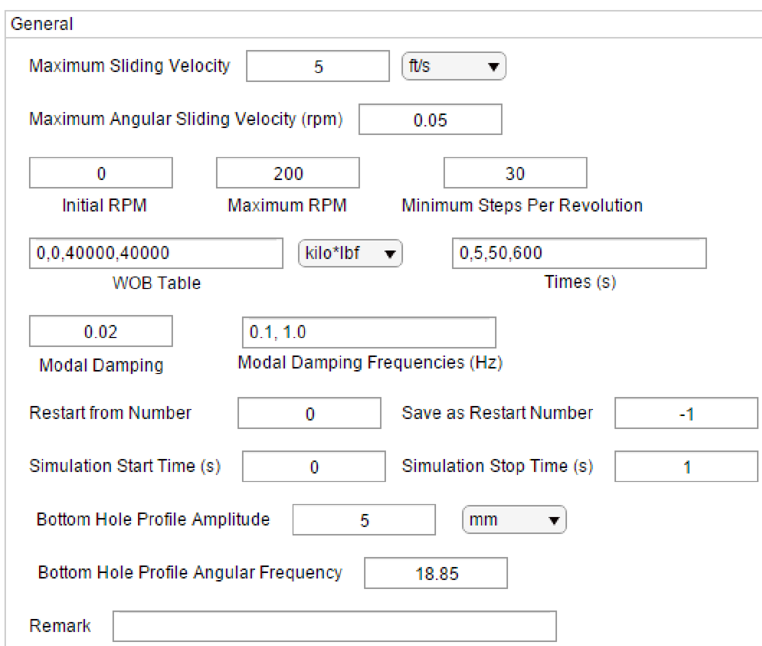


Figure 14 - General Transient Panel

4.3.2 Drillbit Friction

The Drilling Kinetic Friction Coefficient can be set either by directly specifying its value or by enabling 'Calculate Drillbit Friction' and supplying the Confined Compressive Stress, Cutter Diameter and Fluid Mass Density in order to predict it. For direct specification of the drilling friction torque coefficient, these parameters are not needed and are not used.

Drilling Kinetic Friction Coefficient	Kinetic drilling friction torque coefficient, dimensionless. By default, the Drilling Kinetic Friction Coefficient is not given.
Drilling Static to Kinetic Friction Ratio	Ratio of static to kinetic friction at the surface of the cased portion of the borehole. Can also be estimated by enabling 'Calculate Drillbit Friction' and supplying 'Confined Compressive Stress', 'Cutter Diameter' and 'Fluid Mass Density'.
Confined Compress Stress	Confined compressive strength of the rock. This parameter is not used if the drilling friction torque coefficient is supplied as input.
Cutter Diameter	Cutter diameter. This parameter is not used if the drilling friction torque coefficient is supplied as input.
Fluid Mass Density	Mass density of the drilling fluid (mud). This parameter is not used if the drilling friction torque coefficient is supplied as input.

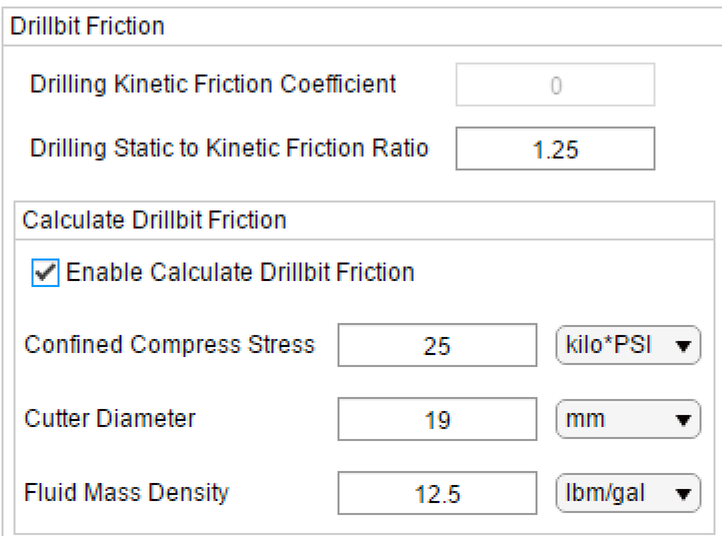


Figure 15 - Drillbit Friction Panel

4.3.3 Case Wall Friction

Friction Coefficient	Kinetic coefficient of friction at the surface of the cased portion of the borehole.
Static to Kinetic Friction Ratio	Ratio of static to kinetic friction at the surface of the cased portion of the borehole.

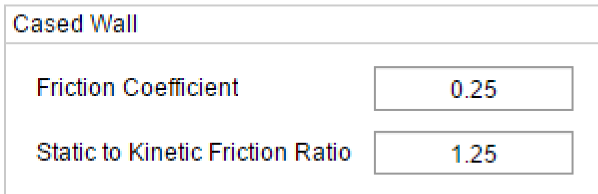


Figure 16 - Cased Wall Friction Panel

4.3.4 Uncased Wall Friction

Friction Coefficient	Kinetic coefficient of friction at the surface of the uncased portion of the borehole.
Static to Kinetic Friction Ratio	Ratio of static to kinetic friction at the surface of the uncased portion of the borehole.

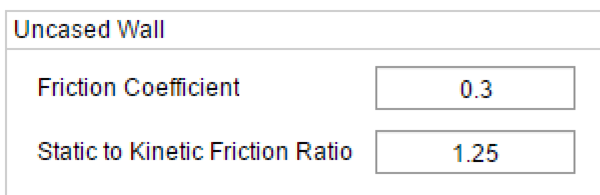


Figure 17 - Uncased Wall Friction Panel

4.3.5 PID Control Parameters

The torque on the bit (TOB) can be controlled either by providing a table of time-TOB pairs or by providing the RPM at the rotary table through a table of time-RPM pairs. Therefore, the user needs to specify Times and Torque tables, or Times and RPM tables. The Torque table and RPM table cannot be specified simultaneously, and so one of them needs to be left empty. When the RPM table is specified, the torque-on-bit control function creates a PID (Proportional, Integral, Derivative) controller with constants given by the three control parameters: Proportional, Integral and Derivative. The weight-on-bit is controlled by prescribing a table of time-WOB pairs in the Transient General Panel.

Proportional	Proportional control parameter of the PID controller for the torque of the rotary table.
Integral	Integral control parameter of the PID controller for the torque of the rotary table.
Derivative	Derivative control parameter of the PID controller for the torque of the rotary table.
Torque Limit	Limit on the torque that can be exerted by the rotary table.
RPM Table	Array of desired RPM values at the rotary table. This works in conjunction with the PID controller of the torque at the rotary table. The controller attempts to apply torque to match the current value of the desired RPM.
Torque Table	Array of TOB (or rather of the torque at the rotary table) values.
Times	Array of times at which TOB (or rather the torque at the rotary table) values or the desired RPM values are given.
Remark	A one line comment to describe the target (optional).

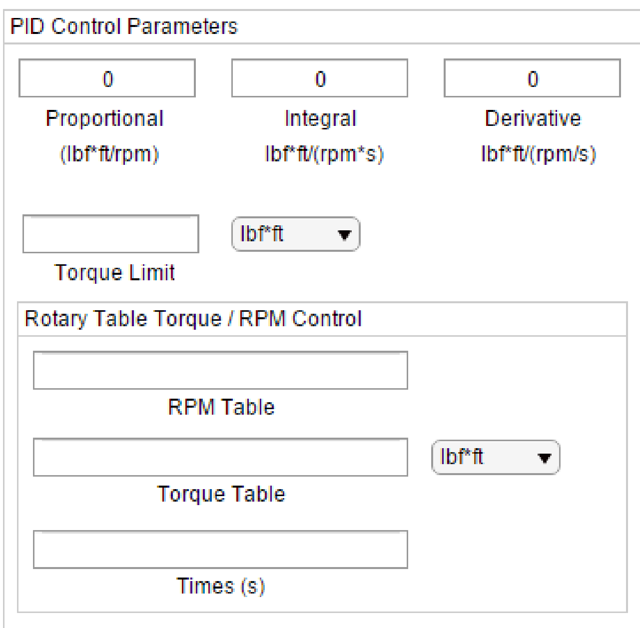


Figure 18 - PID Control Parameters Panel

4.3.6 Rate of Penetration Model

The Rate of Penetration (ROP) model is based on the following formulas:

$$ROP = -ROP\_a1 + (WOB>0) \times ROP\_a2 \times WOB + (Omega\_bit>0) \times ROP\_a3 \times Omega\_bit$$

$$ROP = ROP \times (Omega\_bit > max\_friction\_angular\_velocity)$$

First, the ROP is evaluated from the formula

$$ROP = -ROP\_a1 + (WOB>0) \times ROP\_a2 \times WOB + (Omega\_bit>0) \times ROP\_a3 \times Omega\_bit$$

where

ROP_a1, *ROP_a2*, and *ROP_a3* are parameters of the model

WOB is the weight on bit force.

Omega_bit is the angular speed of the bit.

For both *WOB* and *Omega_bit*, nonzero contribution to the ROP is calculated only when the quantity has the correct orientation. WOB must press the bit into the rock ($WOB>0$), and the angular speed must correspond to the bit turning with the teeth cutting into the rock ($Omega\_bit>0$).

Second, the ROP is assumed to be nonzero only when the bit is turning and the teeth are cutting, which corresponds to the bit rotating with an angular velocity greater than the maximum friction angular velocity. For a value smaller than this velocity, the bit is assumed to be stuck.

$$ROP = ROP \times (Omega\_bit > max\_friction\_angular\_velocity)$$

ROP_a1	Parameter of the ROP (rate of penetration) model. This is the constant term.
ROP_a2	Parameter of the ROP model. This is the proportionality coefficient of the WOB contribution to the ROP.
ROP_a3	Parameter of the ROP model. This is the proportionality coefficient of the angular speed contribution to the ROP.

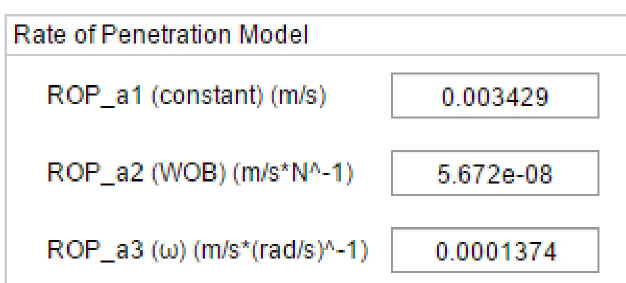


Figure 19 – Rate of Penetration Panel

4.3.7 Transient Cat

This target concatenates results from separate sequential rotate simulation restarts. Previously calculated restarts will be combined by this target into a single data set that can be referred to as yet another restart.

As an example, consider the following scenario: the "*rotate*" target was run four times, once starting from restart 0 to simulate the rotation of the drill string from 0.0 seconds to 5.0 seconds, which was saved as restart 1. Another time to simulate the rotation from 5.0 seconds to 60 seconds, which was saved as restart 2, then rotating from 60 seconds to 120 seconds, which was saved as restart 3, and finally rotating from 60 seconds to 120 seconds with changed drilling parameters, which was saved as restart 4. We would like to analyze the sequence of the simulation runs that resulted in restarts 1,2,4 as a single data set. Thus, the input would be set as in Figure 20.

Using Transient Cat, Restart 5 is equivalent to simulating the rotation of the drill string (under the same conditions which were used in restarts 1,2, and 4) from 0.0 seconds to 120 seconds in a single simulation. Also note that for this concatenation to make sense, the time during which the drill string was moving must consist of contiguous, non-overlapping sub-intervals, in this case 0-5, 5-60, and 60-120 seconds.

Restart List	List of previously stored restarts to concatenate. The restarts to be concatenated must exist (i.e. the "*rotate*" target must have been simulated previously for each of the specified restarts). The simulation time intervals for each restart must be contiguous and must be listed in the order of increasing time. See the example below.
Save as Restart Number	Save the computed data as this restart number. This number cannot be inferred, it must be supplied.
Remark	A one line comment to describe the target (optional).

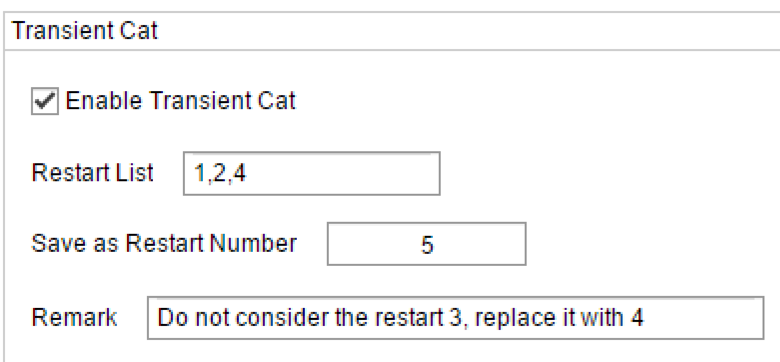


Figure 20 - Transient Cat

4.4 Torque and Drag

The static equilibrium of the drill string under the given set of self-weight, WOB, and hook force was found. The result is a set of normal contact forces between the drill string and the borehole. These forces are converted to friction forces, which when added vectorially will allow the determination of three hook forces: tripping out, tripping in, and static. The friction forces are also converted to friction torques which are added up to estimate the torque at the rotary table needed to turn the drill string against friction.

These hook forces are calculated for a variable composition of the drill string given by the num_components target data. The drill string is repeatedly built up of the desired number of components, equilibrium is iterated, and the hook forces are calculated.

Boundary conditions

At the kelly, spring restraints against lateral displacements are applied and all rotations are penalized by spring constants. At the bit, axial restraint to mimic rock-bit contact is applied. Finally, a hook force is applied at the top in the direction tangential to the borehole curve, with a magnitude that will produce the weight on bit (WOB), as given in the target data. Since the hook force is unknown initially, it needs to be calculated by iteration from the condition of equilibrium.

The function will calculate the friction forces due to the interaction of the drill bit with the borehole walls. If WOB=0, the hook force balances out the drill string without friction. The pickup weight would be this value of the hook force plus all the friction forces between the drill string and the wall.

Fluid Mass Density	Mass density of the drilling fluid.
Drillbit Friction Coefficient	The dimensionless coefficient to calculate the drilling torque from the weight on bit. The drilling torque is produced as a product of the WOB, the radius of the bit, and this coefficient according to the following relationship. *Frictional Torque = drilling_friction_coefficient × WOB × (2/3) × bit_radius*
Cased Wall Friction Coefficient	Friction coefficient for the cased part of the borehole.
Open Hole Wall Friction Coefficient	Friction coefficient for the uncased (open) part of the borehole.
Axial Velocity	Axial speed of drill string motion. Must be nonnegative. Used only in conjunction with nonzero Rotation Speed. Positive axial speed reduces drag torque. The larger the axial speed, the smaller the drag torque.
Rotation Speed	Rotation speed of drill string motion. Must be nonnegative. Used only in conjunction with nonzero Axial Velocity. Positive rotation speed reduces axial drag force. The larger the rotation speed, the smaller the axial drag force.
# of Components	List of the numbers of components to use. If supplied as empty, constructing the drill string successively out of all its components is implied. For instance, if the drill string

	has been defined to have six components, the torque-and-drag simulation will consider the drill string consisting of one, two, three, four, five, and six components.
Weight on Bit	Weight on bit.
Remark	A one line comment to describe the target (optional).

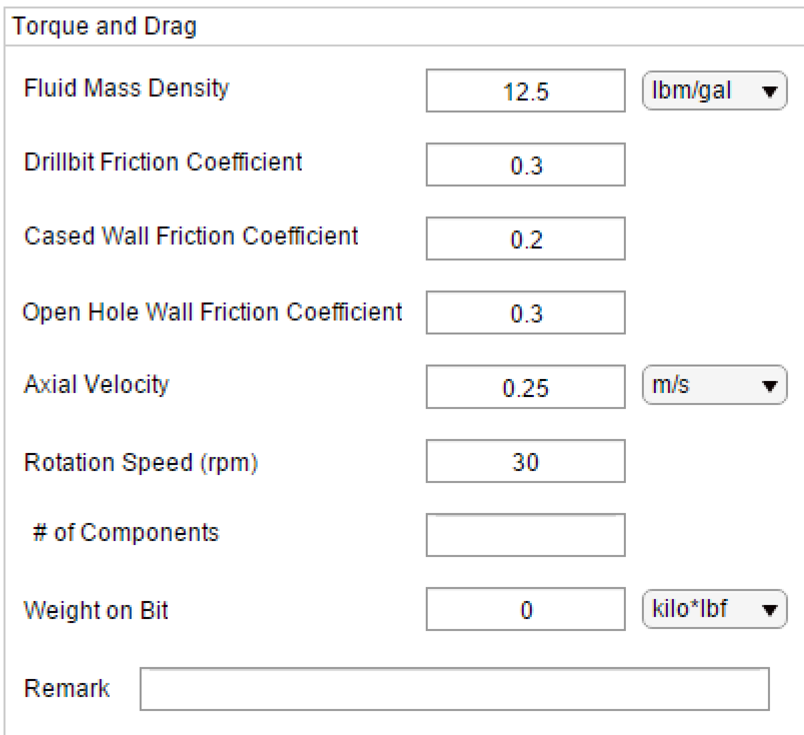


Figure 21 - Torque and Drag Panel

5 Output Control

5.1 General

5.1.1 Image Output Settings

The image output settings panel can be used to specify the properties of the resulting images from the simulations.

Image Format	Image format can be jpg, png or bmp.
Dots Per Inch Resolution	Dots-per-inch resolution of the image.
Image Height	Image height in paper units (points).
Image Width	Image width in paper units (points).

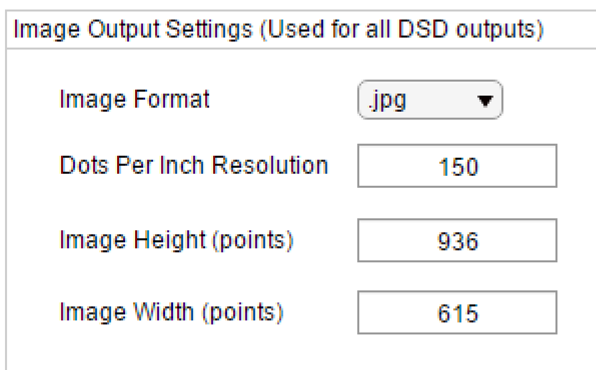


Figure 22 - Image Output Settings Panel

5.1.2 Borehole Profile

The curve representing the borehole profile is plotted in 3-D Cartesian coordinates. The control points are shown as markers.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the horizontal axis.

Remark	A one line comment to describe the target (optional).

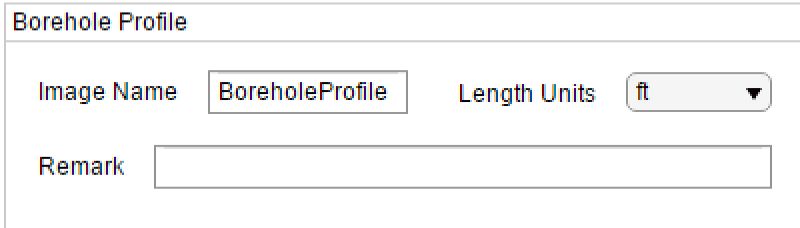


Figure 23 - Borehole Profile Output Options

5.2 Static

5.2.1 Internal Forces

The curves representing the internal force resultants are plotted in a single graph. Different outputs, such as torques and forces, should not be mixed together in a single graph.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the horizontal axis.
Resultant	List of the codes of resultants to be plotted. The individual resultants are N (axial force), S2 (shear force along the local x2 direction), S3 (shear force along the local x3 direction), M1 (torsional moment), M2 (bending moment about the local x2 axis), M3 (bending moment about the local x3 axis), and Mmax (maximum bending moment). The input to the resultant field can be a combination of the symbols above. For instance, resultant =N,S2,S3 or resultant=M2,M3,Mmax.
Resultant Units	Units in which to present the resultant(s). Different resultants (such as forces and torques) should not be mixed together in the same graph.
Target	Name of target for which the internal force should be displayed. The default is selfweight.
Remark	A one line comment to describe the target (optional).

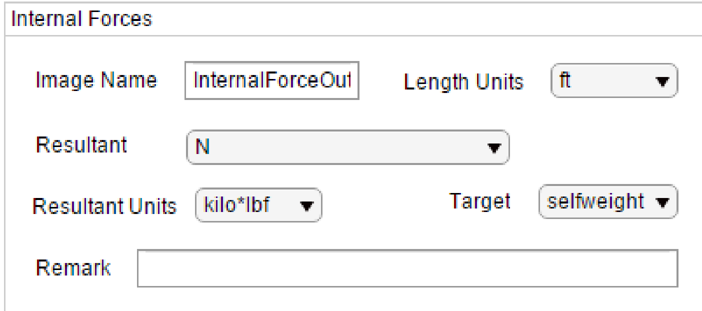


Figure 24 - Internal Forces Panel

5.2.2 Contact Forces

This option produces a plot of the contact forces between the drill string and the borehole. These are only the forces of the frictionless normal contact. The forces are calculated and displayed for the target which was specified as an input. Any target that computes the deformed shape of the drill string is allowed.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the length. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
Force Scale	Numerical factor to scale the length of forces compared to the dimensions of the drill string.
Target	Name of the target for which the contact forces should be calculated and displayed. Any target that computes the deformed shape of the drill string is allowed (i.e. targets setup, selfweight).
Remark	A one line comment to describe the target (optional).

Figure 25 - Contact Forces Panel

5.2.3 Critical RPM

This option produces a plot of the lateral deflection of the drill string under eccentric steady-state rotation conditions. The boundary conditions are as specified for the target Free Vibration. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Deflection Units	Measurement units for the deflections.
Remark	A one line comment to describe the target (optional).

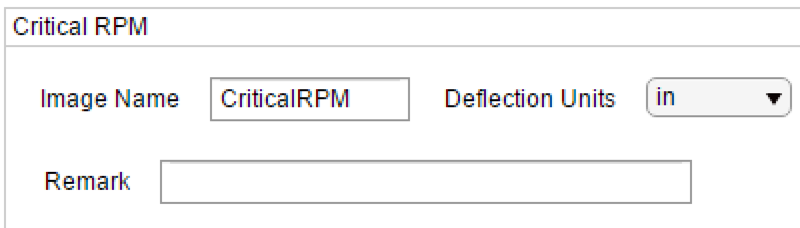


Figure 26 - Critical RPM Panel

5.2.4 Natural Frequencies

This option produces a plot of the free-vibration (natural) frequencies. The boundary conditions are as specified for the target Free Vibration. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Remark	A one line comment to describe the target (optional).

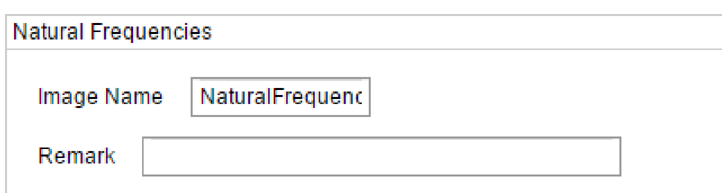


Figure 27 - Natural Frequencies Panel

5.2.5 Mode Shape

This option produces a plot of the free-vibration mode shape. The boundary conditions are as specified for the target Free Vibration.

Image Name	Image name (without extension). The image is saved in the model folder.
Show Local Coords	Boolean flag: should the local coordinate system on each finite element be displayed? Set it to true if the vibration mode is predominantly torsional: the local coordinate systems will make the mode shape much easier to interpret.
Length Units	Measurement units for the lengths.
Length Frac	The magnitude of the mode shape is selected to make the largest amplitude of lateral motion equal to this fraction of the total drill string length. This should be a small value.
Mode Number	Number of mode shapes to plot. Positive integer, less than or equal to the total number of calculated mode shapes.
Remark	A one line comment to describe the target (optional).

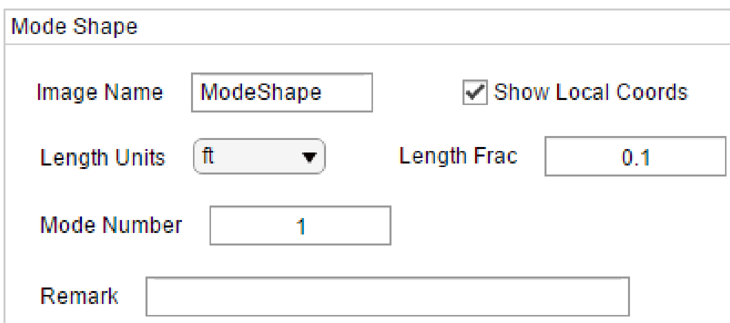


Figure 28 - Mode Shape Panel

5.2.6 Lateral Map

This option produces a 3-D surface plot of the lateral deflection of the drill string under eccentric steady-state rotation conditions. The plot shows the lateral deflection of the drill string under eccentric steady-state rotation conditions as a function of the weight on bit (WOB) and the rotation speed (RPM). The boundary conditions are as specified for the target Free Vibration.

Image Name	Image name (without extension). The image is saved in the model folder.
Deflection Units	Measurement units for the deflections.
Force Units	Measurement units for the WOB forces.
Remark	A one line comment to describe the target (optional).

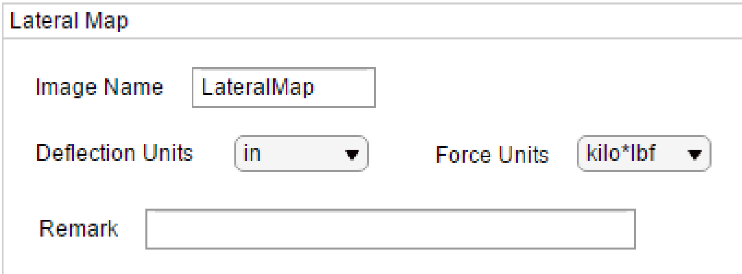


Figure 29 - Lateral Map Panel

5.2.7 Deflection Curve

This option produces a plot of the schematic deflection curve of the drill string. The deflection is the lateral displacement of the drill string in the plane fitted to the borehole curve, which includes the largest lateral displacement of the drill string. Strictly speaking, the curve will be a faithful representation of the deformation of the drill string only for loads that result in a planar deformation of the string. If the drill string deforms into a spatial curve, the present plot is only a crude approximation. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Deflection Units	Measurement units for the deflection. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
Length Units	Measurement units for the lengths.
Target	Name of the target for which deflection curve should be plotted. Any target which computes the deformed shape of the drill string can be specified.

Remark	A one line comment to describe the target (optional).

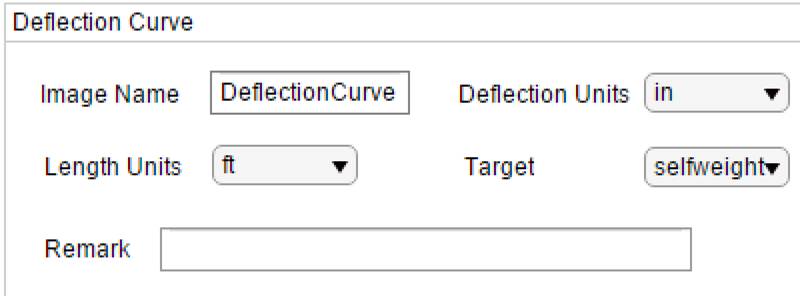


Figure 30 - Deflection Curve Panel

5.3 Transient

5.3.1 Axial Displacement

This option produces a plot of the axial displacements at various locations on the drill string during rotation. The plot shows the axial displacements at selected locations along the drill string as a function of time. The axial displacements are measured along the tangent vectors to the drill string midline. Positive displacement is measured when it occurs in the direction pointing towards the rotary table from the bit. The axial displacement at the relative distance from the bit $0 \leqslant x \leqslant 1$ is marked in the legend of the plot as d=x. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the lengths.
Distance from Bit	List of normalized distances from the bit to the locations at which the axial displacement should be plotted.
Restart Number	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

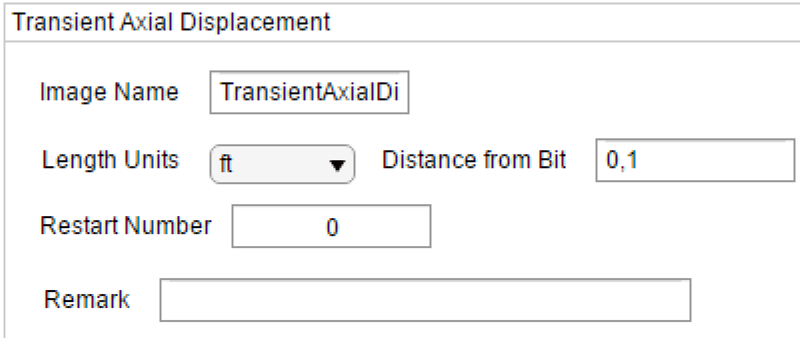


Figure 31 - Axial Displacement Panel

5.3.2 Lateral Displacement

This option produces a plot of the lateral displacements of various locations on the drill string during rotation as a function of time.

The lateral displacements are measured in a Cartesian coordinate system centered at the location of the centroid of the wellbore (casing) cross-section. The coordinate system is established as follows. The tangent vector t to the drill string defines the axial direction, and is the first basis vector of the local Cartesian coordinate system. The direction of gravity acceleration g is compared with the tangent vector t. If the direction of the gravitational acceleration is not parallel to the tangent vector t (i.e. if the drill string midline is not vertical), the two vectors t and g define a vertical plane. The basis vector h of the local Cartesian coordinate system is orthogonal to this plane. The third basis vector, v, completes the triple of orthonormal vectors of the basis, and lies in the vertical plane subtended by t and g. On the other hand, if the direction of the gravitational acceleration is parallel to the tangent vector t (i.e. if the drill string midline is vertical), the vertical plane is defined with a vector along the global Cartesian Y axis instead of the vector of gravitational acceleration. The components of the displacement u_h and u_v are expressed in the basis vectors h and v. Note that when the transverse displacements are plotted at several locations along the drill string, each of the locations will have its own local coordinate system defined as described above.

The lateral displacements at the relative distance from the bit $0 \leqslant x \leqslant 1$ are shown in the legend of the plot as uh@d=x (component on the basis vector h) and uv@d=x (component on the basis vector v).

In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the lengths.
Distance from Bit	List of normalized distances from the bit to the locations at which the axial displacement should be plotted.

Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

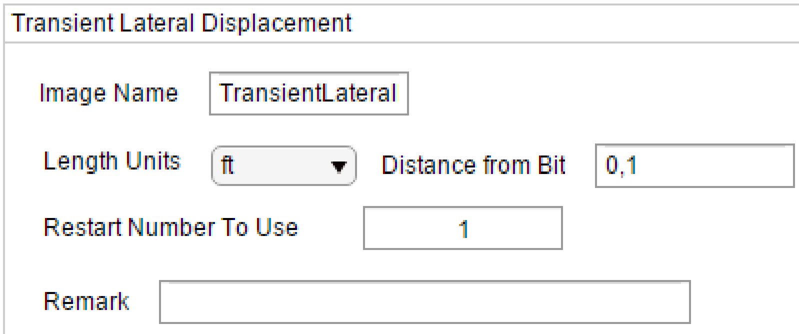


Figure 32 - Lateral Displacement Panel

5.3.3 Rate of Penetration

This option produces a plot of the rate of penetration (ROP) at various locations on the drill string during rotation as a function of time. The model for the calculation of the ROP is described for the "*rotate*" target. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

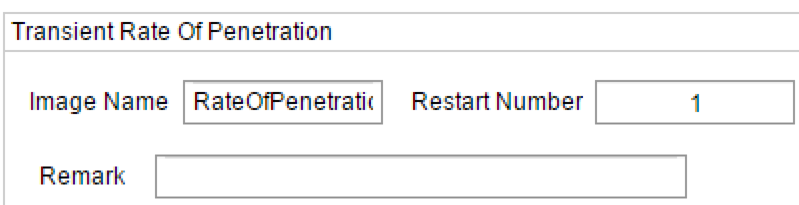


Figure 33 - Rate of Penetration Panel

5.3.4 Weight On Bit

This option produces a plot of the weight on bit (WOB) forces. Both the desired and actual (calculated from simulations) WOBs are plotted. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Force Units	Measurement units for the forces.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

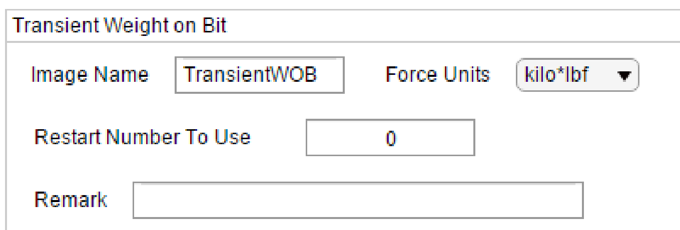


Figure 34 - Weight on Bit Panel

5.3.5 Torque On Bit

This option produces a plot of the torques at the bit and at the top drive during rotation.

Image Name	Image name (without extension). The image is saved in the model folder.
Torque Units	Measurement units for the torques.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

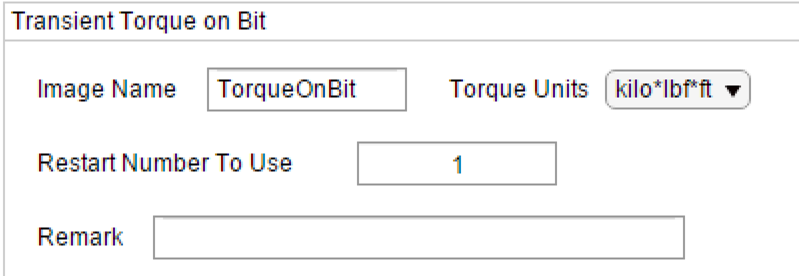


Figure 35 - Torque on Bit Panel

5.3.6 RPM

This option produces a plot of the axial angular velocity in RPM units at various locations on the drill string during rotation. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in the CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the lengths.
Distance from Bit	List of normalized distances from the bit to the locations at which the axial displacement should be plotted.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

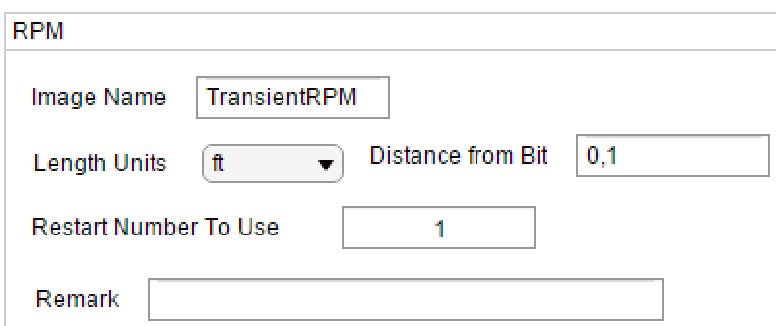


Figure 36 - RPM Panel

5.3.7 Lateral Displacement Orbit Plot

This option produces a plot of the lateral displacements at various locations on the drill string during rotation as a function of time. The coordinate system in which the displacements are measured was described for the target "*show rotate lateral displacement*". This plot shows the displacement along the basis vector *h* versus the displacement along the *v* basis vector. The lateral displacements at the relative distance from the bit $0 \leqslant x \leqslant 1$ are marked in the legend of the plot as d=x. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the lengths.
Distance from Bit	List of normalized distances from the bit to the locations at which the axial displacement should be plotted.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

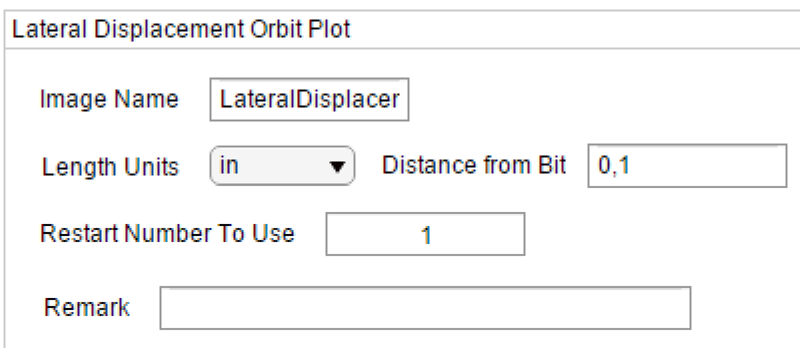


Figure 37 - Lateral Displacement Orbit Plot Panel

5.3.8 Vibration Risk Index

This option produces a plot of the vibration risk index during rotation. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.

Length Units	Measurement units for the lengths.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

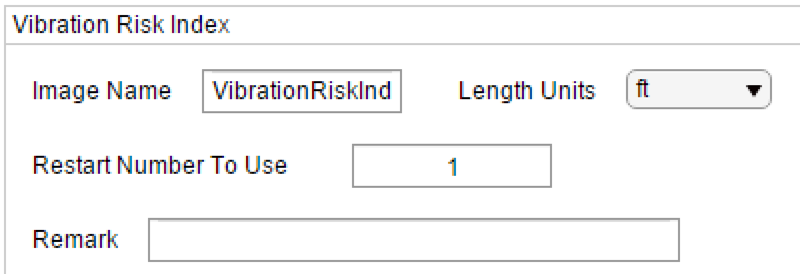


Figure 38 - Vibration Risk Index Panel

5.3.9 Whirl Speed

This option produces a plot of the whirling speeds at various locations on the drill string during rotation as a function of time. Both the axial angular velocity (speed) of the rotating drill string (marked with symbol ωa) and the angular velocity with which the centroid of the drill string rotates about the center of the borehole (designated as the whirling speed, marked with symbol ω) are shown. The rotation speeds are measured in the Cartesian coordinate system described for the target "*show rotate lateral displacement*". The rotation speed is positive when it is turning about the local tangent vector to the borehole midline in the positive sense of the right-hand rule. Therefore, if the axial speed of the rotating drill string is positive, and the whirling speed of the centroid is negative, the motion of the drill string corresponds to a backward whirl. Conversely, if both rotation speeds have the same sign, the motion of the centroid of the drill string corresponds to a forward whirl.

The axial angular velocity at the relative distance from the bit $0 \leqslant x \leqslant 1$ is shown in the legend of the plot as ωa@d=x. Similarly the whirling angular velocity ω@d=x. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Rotation Units	Measurement units for the rotation speeds.

Distance from Bit	List of normalized distances from the bit to the locations at which the lateral displacement should be plotted.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

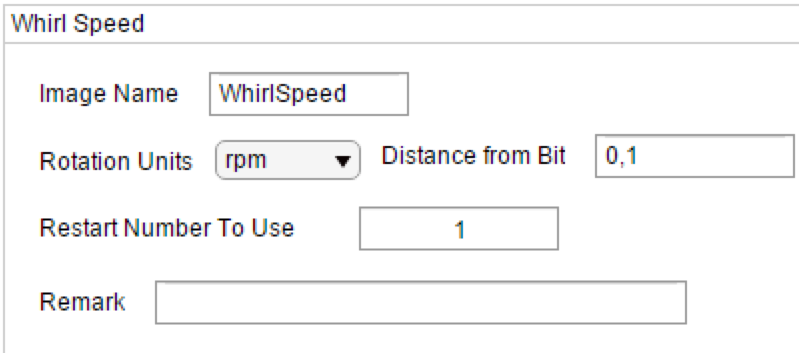


Figure 39 - Whirl Speed Panel

5.3.10 Whirl Indicator

This option produces a plot of the whirl indicator at various locations on the drill string during rotation as a function of time. The whirling indicator WI is defined as:

$$WI = \frac{\text{omega}}{\text{omega}_\text{a}} \text{x} \frac{\text{Radius}}{\text{maxRadius}}$$

where omega is the angular velocity of the center of the drill string as it moves about the center of the borehole, omega a is the axial angular velocity of the drill string about its own axis, Radius is the distance of the drill string center from the center of the borehole, and maxRadius is the radius of the motion of the drill string, at which it contacts the borehole. Refer also to the Figure 40 for an explanation of these parameters.

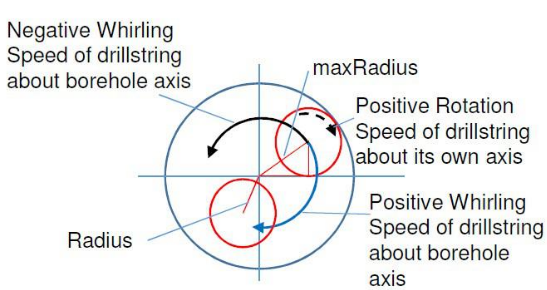


Figure 40 - Whirling

Whirling is established when the magnitude of the whirling indicator is at or above 1.0 (positive or negative). A positive WI indicates forward whirling, whereas a negative WI indicates backward whirling. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Rotation Units	Measurement units for the rotation speeds.
Threshold Amplitude	The whirling indicator is most relevant when the drill string is in contact with the borehole or when the drill string is almost in contact with the borehole. Therefore, we define the whirling indicator to the displayed only if the radius at which the drill string center moves divided by the maximum radius (which defines contact of the drawstring with the borehole) is greater than a supplied threshold ratio. A threshold ratio of 1.0 would mean that the whirling indicator would only be shown for actual contact. A threshold ratio of 0.99 will request the whirling indicator to be shown whenever the drill string is within 1% of the maximum radius.
Distance from Bit	List of normalized distances from the bit to the locations at which the lateral displacement should be plotted.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Remark	A one line comment to describe the target (optional).

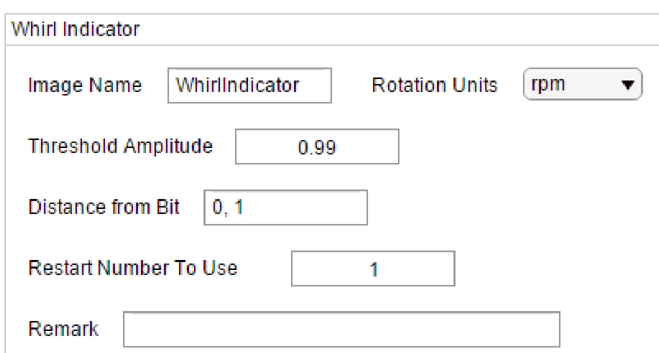


Figure 41 - Whirl Indicator Panel

5.3.11 Simulated Accelerometer

This option produces a plot of the simulated accelerometer reading at various locations on the drill string as a function of time. The accelerations are measured in the direction in which the accelerometer is installed. The location of the accelerometer is described using the position angle and the position radius. The orientation is further described with the orientation angle. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Acceleration Units	Measurement units for the accelerations.
Restart Number To Use	Load the restart data of the transient target for the specified restart number. The restart number is in general > 0; and an error occurs if a restart that does not exist is specified.
Distance from Bit	List of normalized distances from the bit to the locations at which the lateral displacement should be plotted.
Position Angles	An array of position angles, one for each accelerometer. This angle is measured between the radial line arbitrarily taken along the local *h* axis and the radial line that connects the accelerometer with the centroid of the drill string cross-section. The array of position angles [0,120,240] [deg] corresponds to 3 accelerometers uniformly distributed around the circle.
Position Radii	Radius at which the accelerometer is positioned (i.e. distance from the centroid of the cross-section).
Orientation Angles	An array of orientation angles, one for each accelerometer. This angle is measured between the radial line connecting the accelerometer and the centroid of the drill string cross-section. An angle of 0 means that the accelerometer is oriented radially, while an angle of 90 means that the accelerometer is oriented circumferentially.
Remark	A one line comment to describe the target (optional).

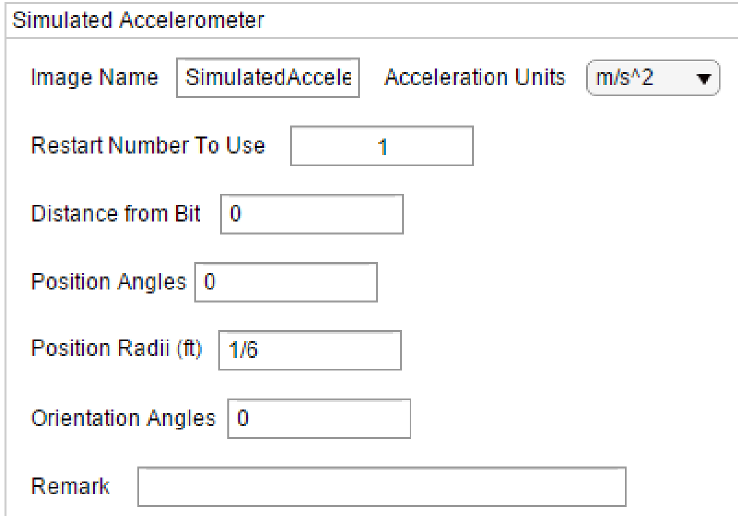


Figure 42 - Simulated Accelerometer Panel

5.4 Torque And Drag

5.4.1 Drag Forces

The plot shows the hook force for the three modes of operation of the drill string: rotating off-bottom, pick up (tripping out), and drop-in (tripping in), for a successively increasing number of components of the drill string, and hence for a successively increasing measured depth. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the measured-depth axis.
Force Units	Units in which to express the hook force.
Travelling Mass Block	Mass of the traveling block.
Remark	A one line comment to describe the target (optional).

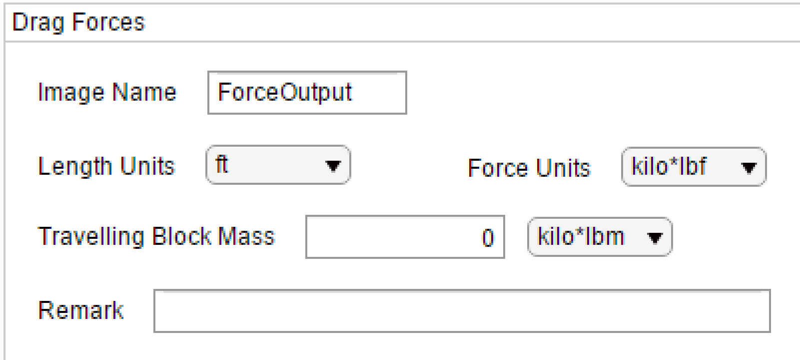


Figure 43 - Drag Forces Panel

5.4.2 Drag Torques

The plot shows the torque required to rotate the drill string off-bottom for a successively increasing number of components of the drill string, and hence for a successively increasing measured depth. In addition to an image of the graph, the data is also saved as an Excel spreadsheet in CSV format.

Image Name	Image name (without extension). The image is saved in the model folder.
Length Units	Measurement units for the measured-depth axis.
Torque Units	Units in which to express the torque.
Remark	A one line comment to describe the target (optional).

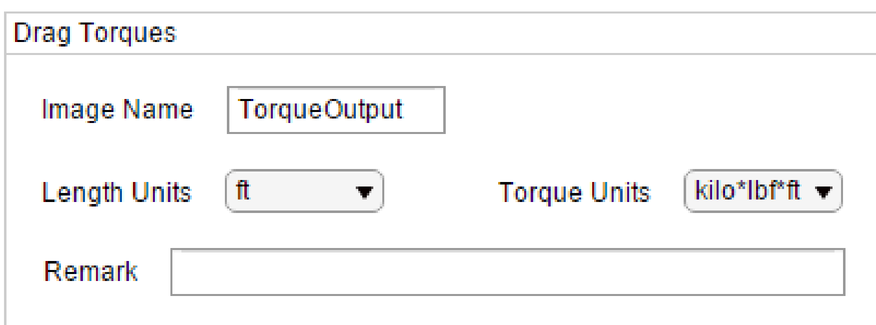


Figure 44 - Drag Torques Panel

6 Results

The results tab displays all images in specified output folder; the user can click on an image to open it in an external image viewer. The 'Open Output Folder' opens the output folder which also contains the .csv output files.

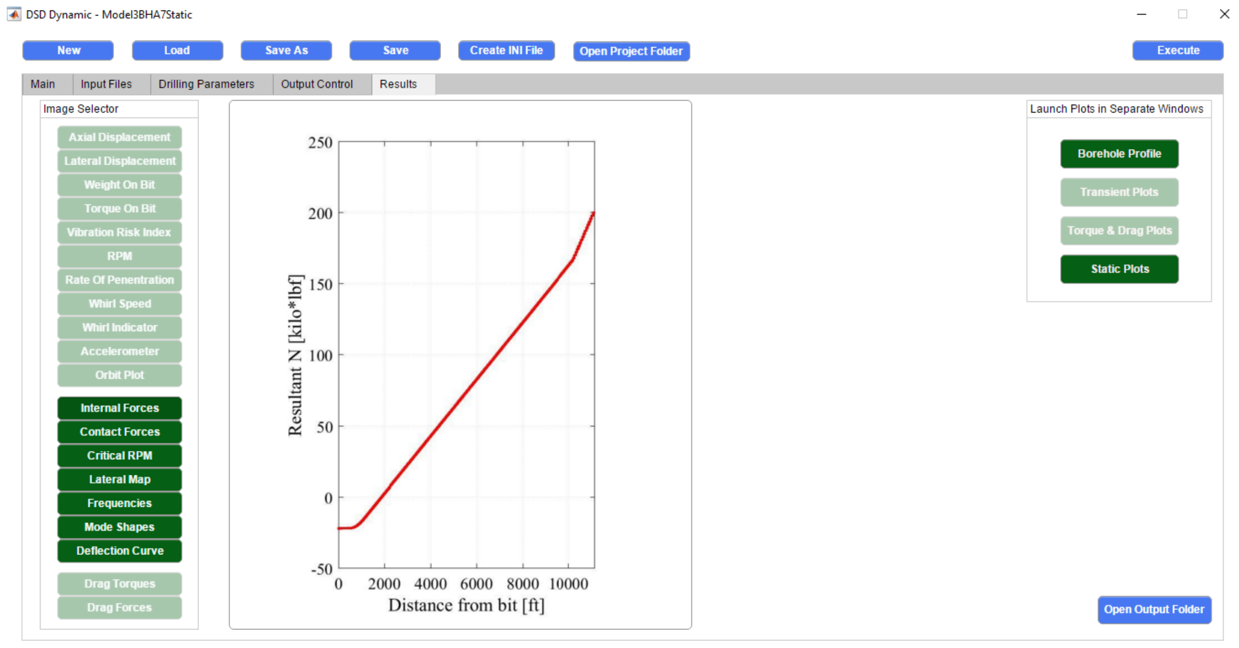


Figure 45 - Results Tab

7 Sample Runs

This section includes test runs of the DSD program that show the various input parameters in the GUI, as well their respective results. For each of the test cases, drill string and well survey files were used. The well survey files were omitted from the following sections for brevity. Furthermore, any parameters not shown were left as empty or were deactivated.

7.1 Test Case 1

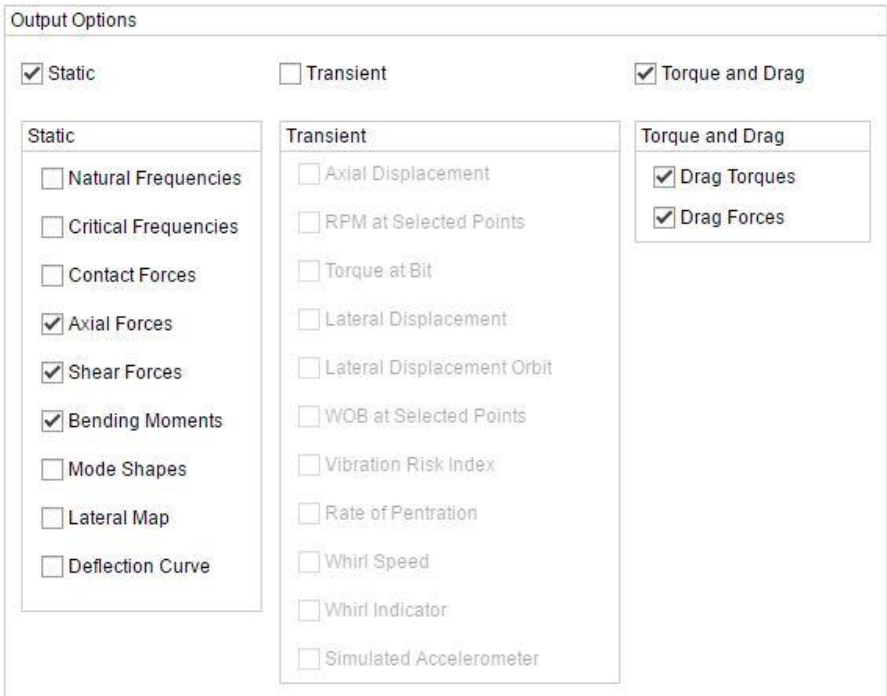


Figure 46 - Test case 1: Output options

Component	Cylinder	Young's Modulus	Poisson's Ratio	Mass Density	External Radius	Internal Radius	Arclength	TJOR
Bit	Cylinder 1	2.05E+11	0.3	7800	0.155575	0.0381	0.371856	
Stabilizer	Cylinder 2	2.05E+11	0.3	7800	0.1174	0.0381	17.03	
NM Stab	Cylinder 3	2.05E+11	0.3	7800	0.104	0.0355	51.84	
HWDP	Cylinder 4	2.05E+11	0.3	7800	0.084	0.057	149.047	
DP	Cylinder 5	2.05E+11	0.3	7800	0.084	0.069	3589.63	

Figure 47 - Test case 1: Drill string input file

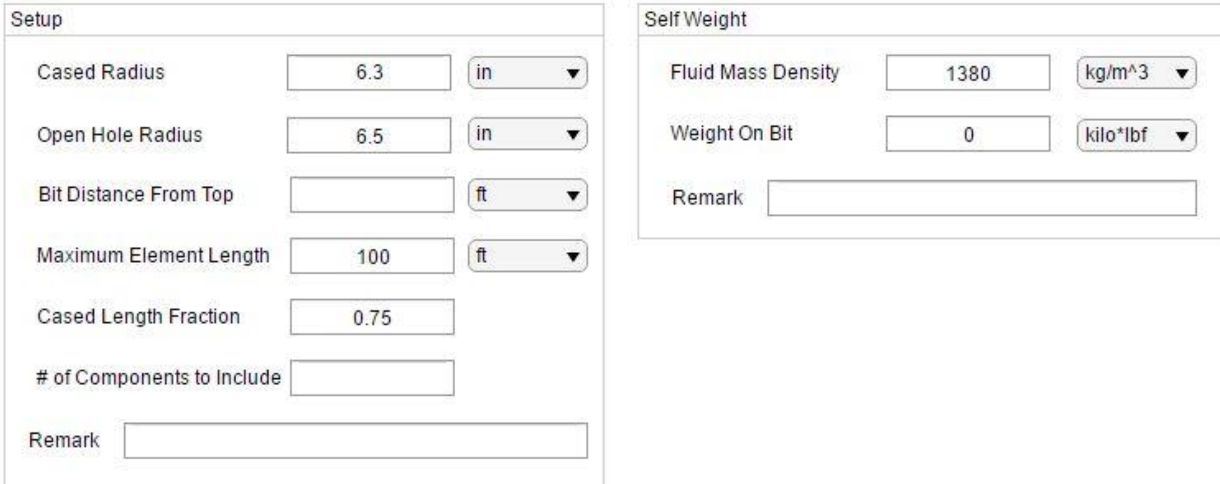


Figure 48 - Test case 1: General drilling parameters

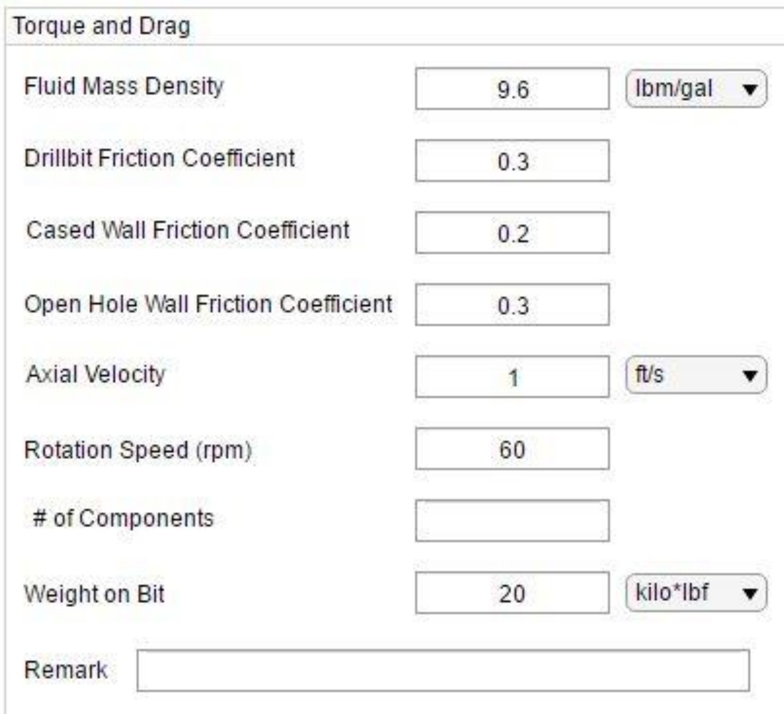


Figure 49 - Test case 1: Torque and drag drilling parameters

Figure 50 - Test case 1: Borehole profile output control

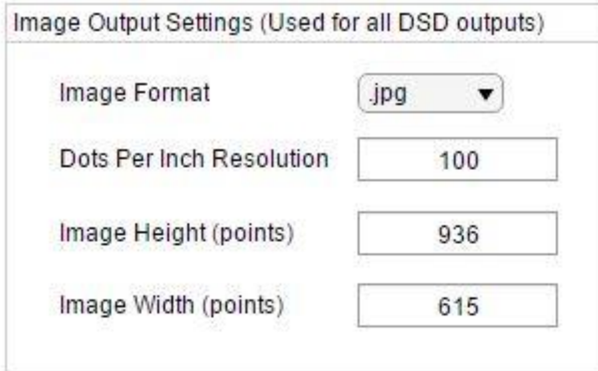


Figure 51 - Test case 1: Image output settings

Figure 52 - Test case 1: Internal forces output settings

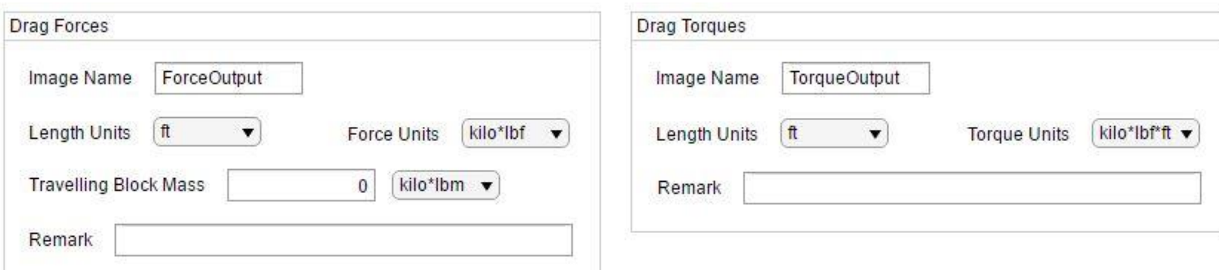


Figure 53 - Test case 1: Drag and torque forces output settings

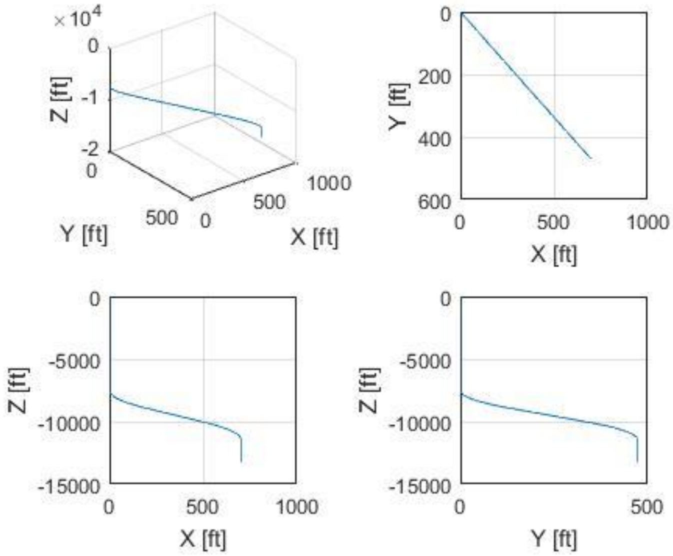


Figure 54 - Test case 1: Borehole profile output

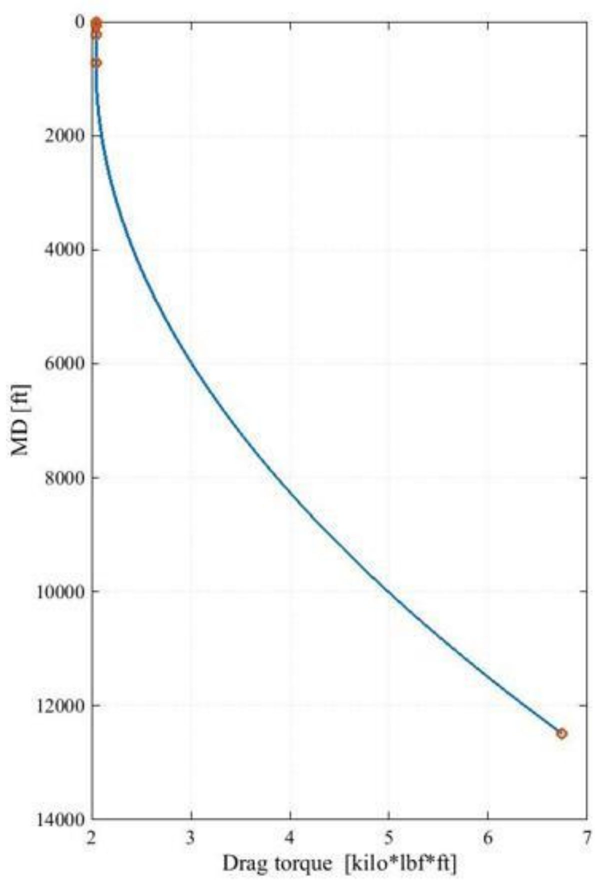


Figure 55 - Test case 1: Torque output

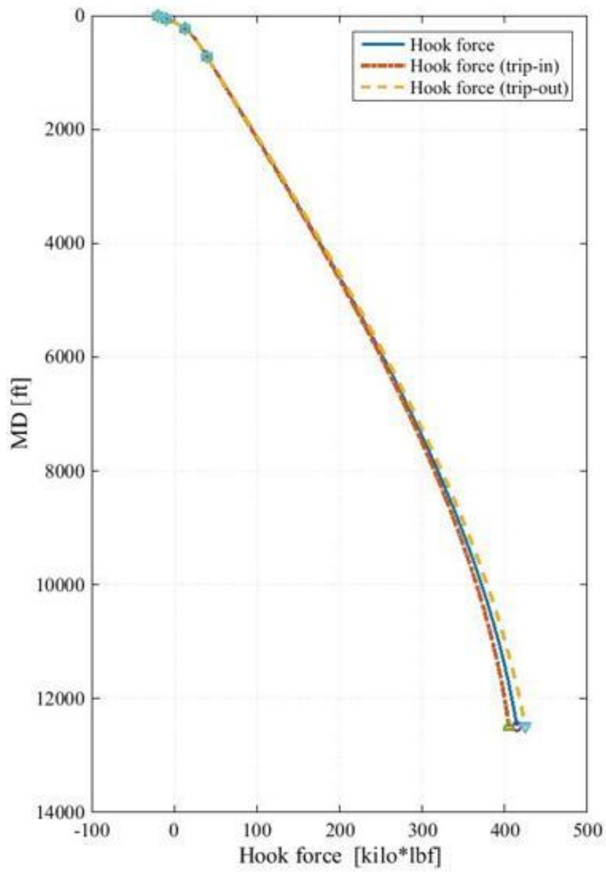


Figure 56 - Test case 1: Force output

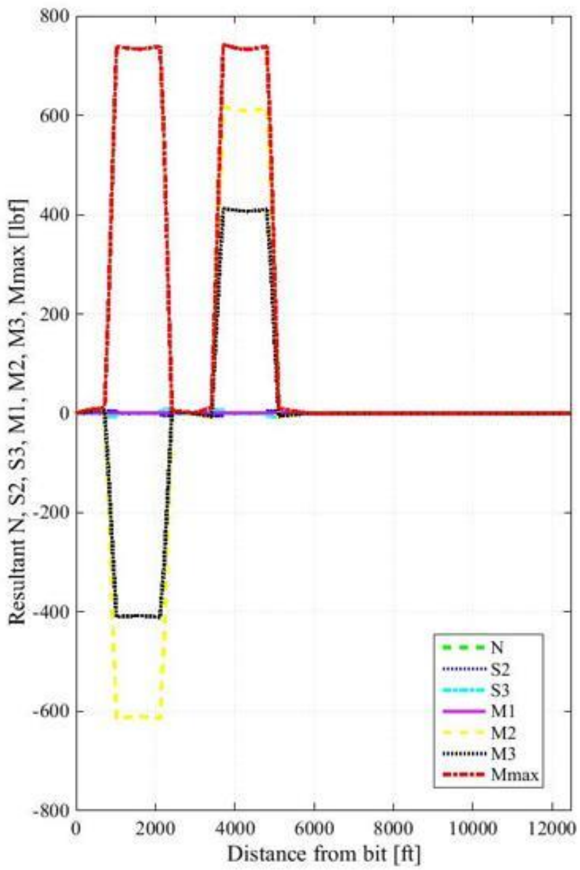


Figure 57 - Test case 1: Internal forces output

7.2 Test Case 2

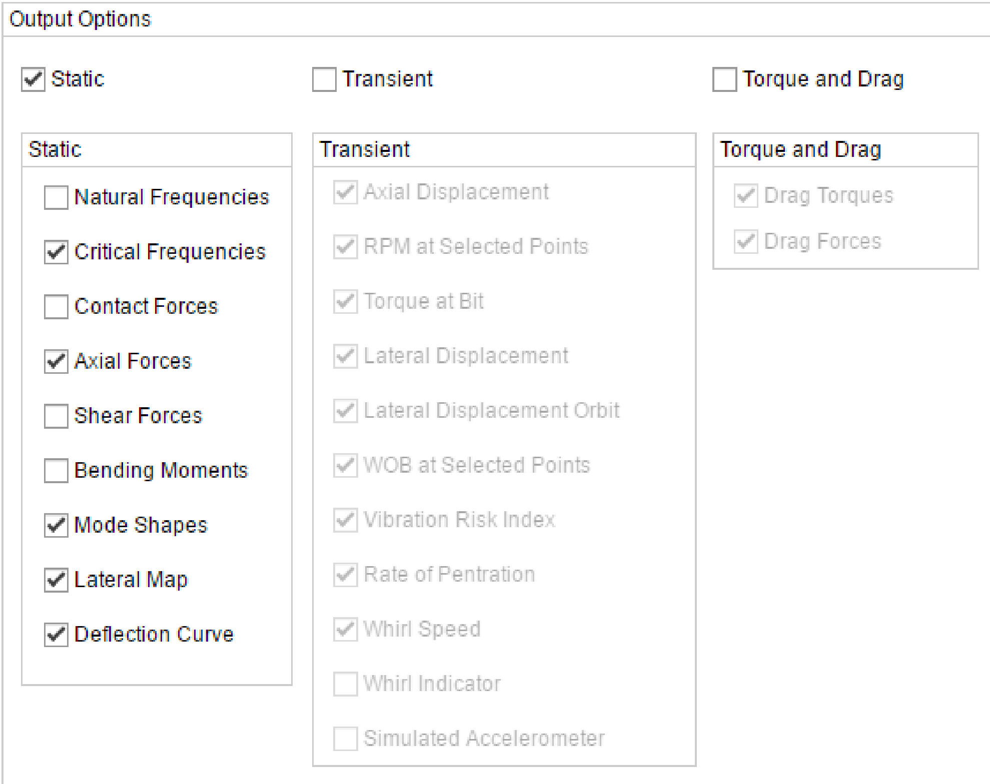


Figure 58 - Test case 2: Output options

Component	Cylinder	Young's Modulus	Poisson's Ratio	Mass Density	External Radius	Internal Radius	Arclength	TJOR
Bit	Cylinder 1	2.05E+11	0.3	7800	0.0762	0.0373126	0.3048	
Motor	Cylinder 2	2.05E+11	0.3	7800	0.0627126	0.0373126	7.641336	
Stabilizer	Cylinder 3	2.05E+11	0.3	7800	0.0627126	0.0373126	1.210056	
Float Sub	Cylinder 4	2.05E+11	0.3	7800	0.0635	0.034925	0.9144	
Collar	Cylinder 5	2.05E+11	0.3	7800	0.0611251	0.034925	3.23088	
Ubho Sub	Cylinder 6	2.05E+11	0.3	7800	0.0587375	0.028575	0.932688	
Collar	Cylinder 7	2.05E+11	0.3	7800	0.060325	0.034925	9.378696	
Collar	Cylinder 8	2.05E+11	0.3	7800	0.060325	0.034925	9.467088	
Stabilizer	Cylinder 9	2.05E+11	0.3	7800	0.0595376	0.034925	1.277112	
Crossover Sub	Cylinder 10	2.05E+11	0.3	7800	0.0627126	0.0333375	0.938784	
Drill Pipe	Cylinder 11	2.05E+11	0.3	7800	0.0508	0.0333375	646.514328	
Scout Safety J...	Cylinder 12	2.05E+11	0.3	7800	0.0611251	0.028575	1.030224	
Scout Pulser	Cylinder 13	2.05E+11	0.3	7800	0.0611251	0.034925	3.986784	
Scout Amplifier	Cylinder 14	2.05E+11	0.3	7800	0.0611251	0.034925	3.374136	
Drill Pipe	Cylinder 15	2.05E+11	0.3	7800	0.0508	0.0333375	2421.709152	
Heavy Weight...	Cylinder 16	2.05E+11	0.3	7800	0.0619125	0.0333375	280.580592	

Figure 59 - Test case 2: Drill string input file

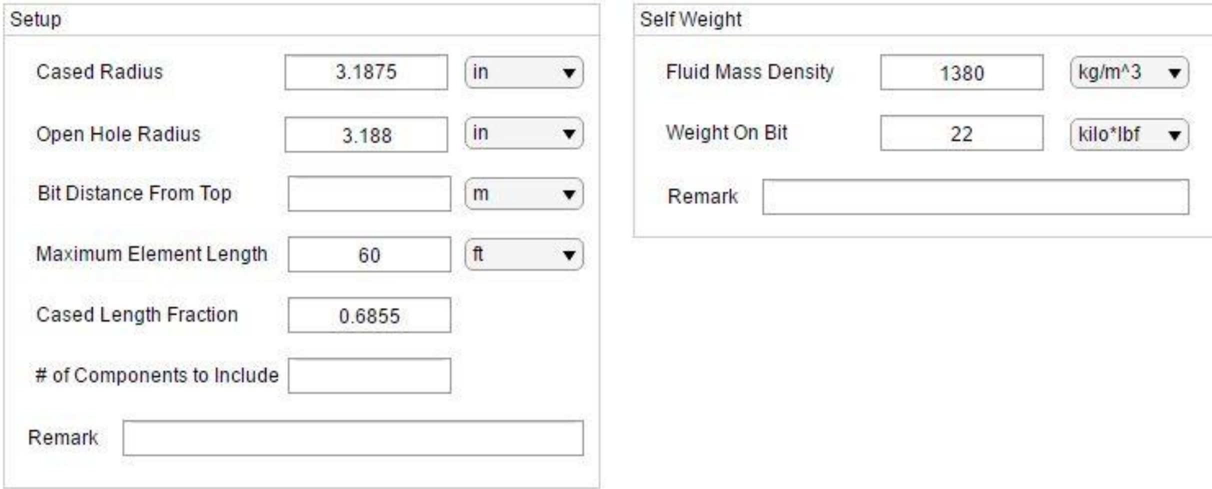


Figure 60 - Test case 2: General drilling parameters

Figure 61 - Test case 2: Static drilling parameters

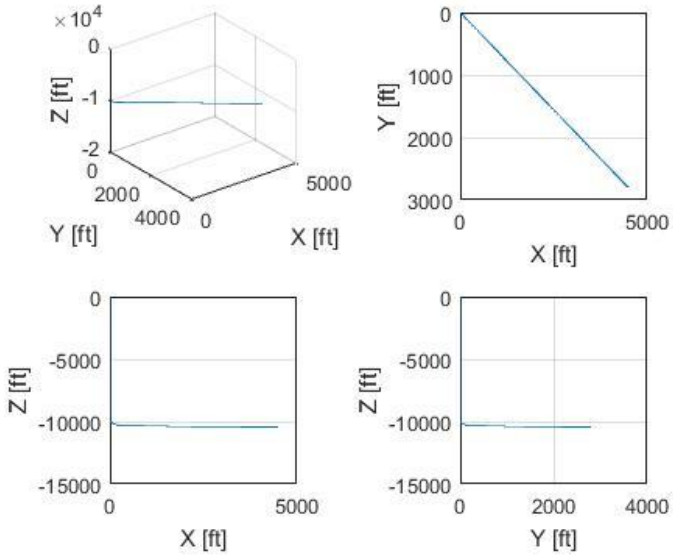


Figure 62 - Test case 2: Borehole profile output

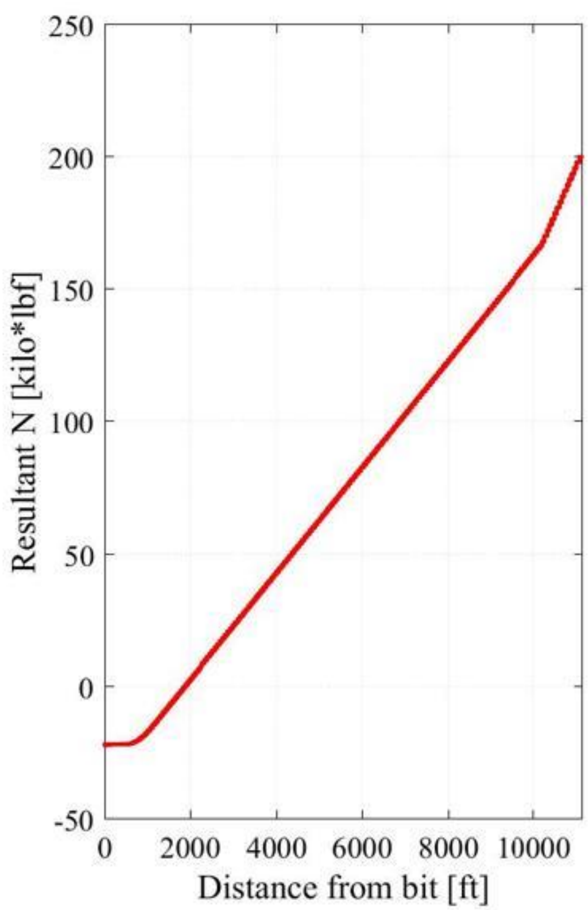


Figure 63 - Test case 2: Internal force output

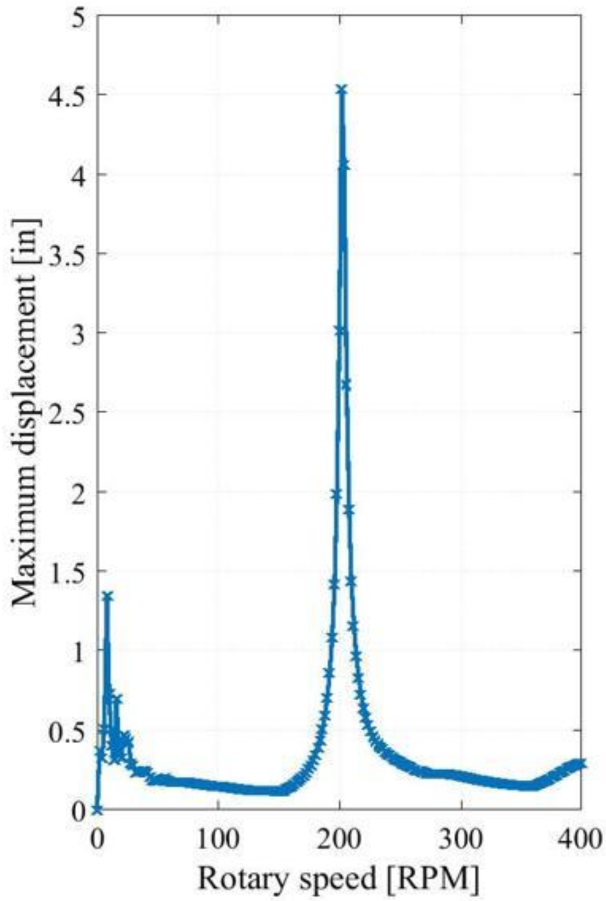


Figure 64 - Test case 2: Critical RPM output

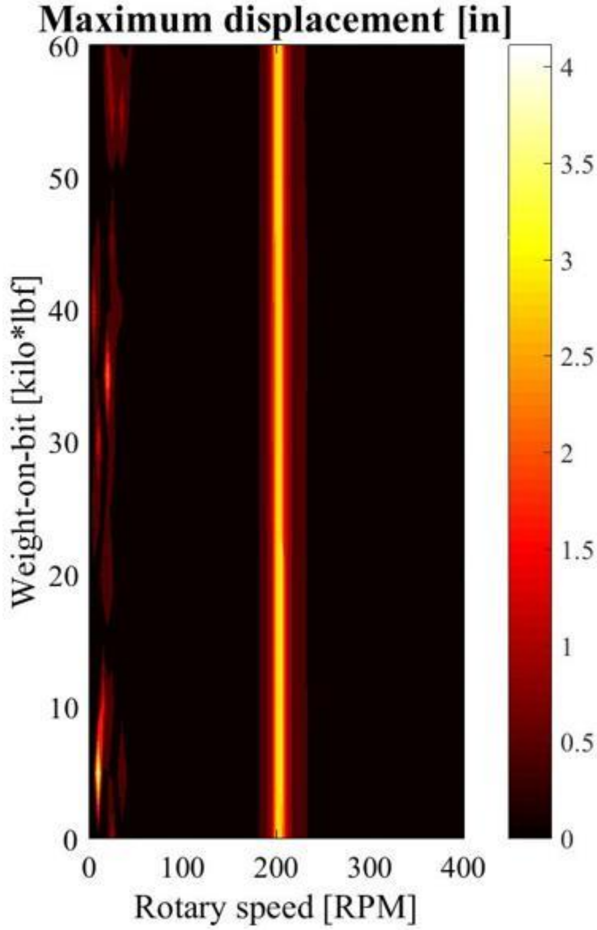


Figure 65 - Test case 2: Lateral map output

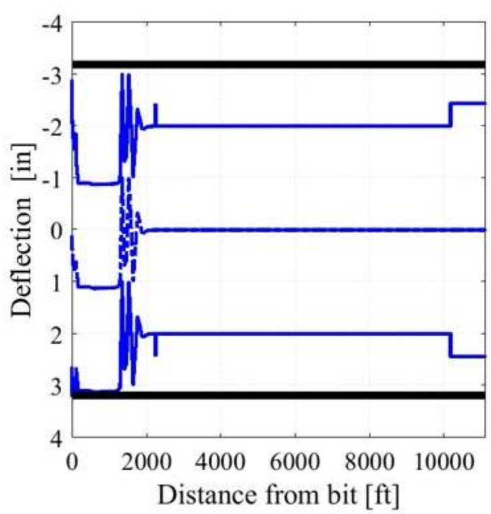


Figure 66 - Test case 2: Deflection curve output