Drillstring Dynamics (DSD)
Vibration and Dynamic Rotation Module
User's manual

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Introduction

1.1 What is DSD?

DSD is an application for drillstring statics and dynamics. DSD simulates the interaction of the drillstring with the borehole under a variety of steady-state (static) and transient dynamic conditions.

DSD can place the drillstring in a given borehole, and calculate its equilibrium configuration (deflections, internal forces, and contact forces with the borehole). DSD can then simulate steady-state rotation of the drillstring 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 drillstring rotating in the borehole. Weight on bit, torque at the top drive or RPM, and the properties of the friction interactions along the surface of the borehole or at the bit can be controlled. The transient dynamics can be simulated in stages to analyze complex drilling scenarios.

DSD can report results in graphical form and as spreadsheets to allow for further postprocessing. 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, vibration risk index plots and so on.

1.2 Methods and Software

DSD is based on the finite element method. The drillstring 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 drillstring and the borehole is represented by a variety of specialized contact models.

The finite element model is implemented in Matlab. The description of the general machinery of finite element (FE) calculations and of the finite element formulation of geometrically nonlinear 3-D beams is not part of this manual. The formulation of the mechanics of drillstrings interacting with a wellbore under a variety of loads is implemented in the program DSD, which built upon the foundation of the above FE methods. The present document is the user's manual for the operation of the program DSD.

1.3 Building process and targets

The DSD understands the process of simulating the various stages in the mechanical deformation of the drillstring as a sequence of targets. Under the term ***target*** we understand here a well-defined computational result. The target may be a *simulation database* representing a particular stage (for example `rotate`) or a *visualization* of the results of a particular stage (for example `show_rotate_rpm`).

The target `T` we are interested in could depend on another target. This information gives DSD the intelligence to build all intermediate targets needed to obtain `T`, and only those targets. 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 be started to deliver the target `show_critical_rpm`, and it will realize that this target depends on the target `critical_rpm` (recall that at this point this target has not been built yet). `DSD` will automatically start to build the target `critical_rpm`, and, as `DSD` promptly finds out, it doesn't exist yet and `DSD` consequently starts to build this target. The target `critical_rpm` in its turn depends on the target `setup`, and since this target doesn't exist either, `DSD` starts to build `setup`. The target `setup` does not depend on any other target and `DSD` can proceed to build it. Once `setup` is built, `DSD` can backtrack to build the target `critical_rpm`, which, once it is available, allows `DSD` to build target `show_critical_rpm`.

Importantly, this approach allows the `DSD` program to build or re-build only 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 if its timestamp is fresher than the current timestamp in the build context, and if the target data has not changed, then the target is deemed not to be in need of rebuilding.
- If a target database does not exist at this point, or if the target database exists and if the current target data does not match the target data in the database, the target needs to be rebuilt.

As an example, consider the following situation. `DSD` needs to build the target `modal`. It checks the target `selfweight`, which in turn depends on the target `setup`. Let us assume that the target `setup` exists and for some reason was in the meantime rebuilt so that its timestamp is fresher than the timestamp of the target `selfweight`. Therefore `DSD` 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 target data of the target `setup`: When the dependency of the target `selfweight` is checked, `DSD` looks at the target `setup` and sees that the target data specified for this target is changed with respect to the target data for which the target `setup` was originally built. Therefore the target `setup` is rebuilt, and consequently the target `selfweight` is also rebuilt as the target on which it depends (`setup`) has changed. Finally the target `modal` can be built.

1.4 Target data and the INI file

The targets are described to the `DSD` program in the so-called INI file. The control parameters are referred to as target data. An example of the INI file is shown here:

```
[setup]
bit_distance_from_top =  2000 [ft]
cased_length_fraction =  0
cased_radius =  0.15557+0.007 [m]
drillstring_file =  DrillstringModel1.csv
input_folder =  ./in
max_element_length =  90.0 [ft]
model_name =  Annotated_Example_1
output_folder =  ./out
survey_listing =  SurveyListing_sample_model_3.csv
uncased_radius =  0.15557+0.007 [m]

[selfweight]
mass_density_of_drilling_fluid = 1380 [KG/M^3]
WOB = 0 [lbf]

[critical_rpm]
```

```
eccentricity = 0.1[in]
RPM_range = 0,400 [rpm]
RPM_step = 5 [rpm]
TOB = 500 [lbf*ft]
WOB = 5000 [lbf]

[show_critical_rpm]
deflection_units = in
image_name = critical_rpm.jpg
[lateral_map]
eccentricity = 0.1[in]
RPM_range = 0,400 [rpm]
RPM_step = 2[rpm]
TOB = 500[lbf*ft]
WOB_range = 0,40 [kilo*lbf]
WOB_step = 2 [kilo*lbf]
```

The INI file consists of blocks, one block per target. The targets are named in the square brackets, such as the target `setup` in the first line [`setup`]. Underneath the line that names a target the target data is listed in arbitrary order. For instance the line

```
cased_radius = (9+5/8)/2 [in]
```

supplies value $(9 + 5/8)/2 \approx 4.8125$ to the target data `cased_radius` in the measurement units of inches.

Note that a target to be built does not necessarily need to be described in the INI file: if the defaults for the target data meet the user's needs, there's no need to include the target in the file.

1.5 Model folder

All the files that describe the state of any of the targets for a particular model are stored in the model folder. The model folder is a subfolder of the `output_folder` as specified for the `setup` target.

The model folder name is the parameter `model_name` of the `setup` target. Only model names with characters `a-z`, `A-Z`, underscore (`_`), `0-9`, space ( ), period (`.`), hyphen (`-`), plus (`+`), equal sign (`=`), and comma (`,`) are admissible.

Here is an example of model folders `Example1` and `Example2`. They are subfolders of the output folder `output_folder` specified as `C:\Users\TheUser\out`.

```
C:\Users\TheUser\out
                |-- Example1
                |-- Example2
```

1.6 Measurement units

The following list includes all the predefined measurement unit symbols that can be used to supply measurement units to the `DSD` program. The capitalization of the letters of the symbol does not matter, so that the following are equivalent `mm`, `Mm`, `MM`.

Time measurement units:

```
SEC, S = second
MIN = Minute
```

```
HR = hour
DAY = Day
WK = Week
MONTH = Month
YR = Year
```

Measurements of angles:

```
RAD=Radian (angle)
DEG=Degree (angle)
REV=Measure of angles in terms of revolutions
```

Length measurement units:

```
M=Meter
IN=Inch
FT=Foot
NMI=Nautical mile
CM=Centimeter
YD=Yard
MM=Millimeter
MILE=Mile
```

Temperature measurement units:

```
K= Degrees Kelvin
RAN= Degrees Rankine
```

Mass measurement units:

```
SLUG=Slug
KG=Kilogram
GM=Gram
```

Force measurement units:

```
N=Newton
OZ=ounce
LBF= Pound of force
KIPS = Thousands of pounds force
```

Measurement units of speed:

```
KT=knot
MPH=mile per hour
```

Measurement units of stress and pressure:

```
PSI=Pounds per square inch
KPSI=Thousands of pounds per square inch
Pa= Pascal
MPa= Millions of Pascal (mega Pascal)
BAR=Bar
ATM=Atmosphere
```

```
TORR=torr
mmHG=mm Hg
BA=CGS unit of pressure, dyne/cm^2
```

Measurement units of work and power:

```
J= Joule
CAL = Calorie
MEV = Mega electron volt
ERG = erg
BTU = BTU
W=watt
MW = Megawatt
HP=Horsepower
```

Measurement units of electrical quantities:

```
COUL=Coulomb (charge);
A = ampere
V = volt
```

Measurement units of frequency and revolutions:

```
HZ = Frequency (Hertz)
RPS = Revolutions per second
RPM =  Revolutions per minute
```

Measurement units of volume:

```
L = Liter
GAL = Gallon
GPM = Gallons per minute
```

Quantitative modifiers:

```
NANO=10^(-9)
MICRO=10^(-6);
MILLI=10^(-3);
KILO=10^3;
MEGA=10^6;
GIGA=10^9;
TERA=10^12;
```

Predefined constants:

```
G=Gravity acceleration
```

Expressions may be formed from the predefined measurement unit symbols using common arithmetic operators. In the INI files the units are always supplied in square brackets. Therefore the following shows a few well-formed measurement unit specifications in square brackets.

```
[ft]
[m/s]
[lbf]
[KG/M^3]
[Kilo*N*m]
[lbf*ft]
```

1.7 How to run DSD

DSD is a compiled application which needs to 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 build. As an example, this line will invoke DSD to build the target **selfweight**, with the description of the targets 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, this 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
```

1.7.1 Logs

DSD writes a log 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 a more detailed information, and only for the particular model in question. 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 drillstring
  DrillstringModel1.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 drillstring 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 on purpose 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]
drillstring_file = DrillstringModel1.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 (returns the status of 0). The log in the working folder then can be inspected:

```
--- 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
```

---

and the offending line can be tracked in the INI file.

1.7.2 Progress file

`DSD` also writes a progress file in the model folder. For each simulation that takes more than a few seconds this file records the name of the operation currently executing, and the progress in percent. The name of the file is composed of the name of the model and the extension `.pgs`. For example, here are the contents of the progress file for an executing `rotate` target which is 99% finished:

```
Rotating
99
```

2

Simulation targets

2.1 Target `setup`

This target establishes initial static equilibrium of the drill string inserted into the borehole. This is the first target to build for any simulation.

2.1.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[setup]
bit_distance_from_top = [] [ft]
cased_length_fraction = 0
cased_radius = [] [in]
drillstring_file = drillstring.CSV
input_folder = ./in
max_element_length = 45 [ft]
model_name = No-name
num_components_to_include= []
output_folder = ./out
remark =
survey_listing = survey_listing.CSV
uncased_radius = [] [in]
```

2.1.2 Description of target data

- `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 distance from the topis implied which would put the top of the drill string at the surface.
- `cased_length_fraction`
  Fraction of the length of the borehole that is cased, non-dimensional. The value must be between zero and one, inclusive.
- `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.

- `drillstring_file`
  Comma-Separated Value (CSV) spreadsheet that describes the drillstring 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. Here is an example of a 10-component drillstring, each component consisting of a single cylinder. Note that the 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

  Here the abbreviations in the first line of the file stand for: `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, `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 input.
  Here is an example of a 8-component drillstring, each component consisting of one or more cylinders. Note that the elastic properties may be specified for each cylinder or only 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

- `input_folder` Name of the folder that holds the input files.

- `max_element_length` Maximum allowed length of a finite element in the mesh of the drillstring tubulars. Except for very 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.
- `model_name` Name of the model.
- `num_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 `num_components_to_include` are taken from the drillbit file to comprise the drillstring for the simulation.
- `output_folder`
  Name of the folder to hold the output folder for the model.
- `remark`
  A one line comment to describe the target (optional).
- `survey_listing`
  The data are read from the survey listing file with the following structure:
  The SurveyListing.csv file
  A survey listing file is a 3-column, comma-delimited text file which specifies the length and orientation of the borehole within which the BHA will be placed and analyzed. Survey listings can be in one for three formats; Cartesian, Polar and single-point survey. Both the format and units are automatically detected. Units of length can in either feet (specified by the abbreviation ft) or meters (specified by the abbreviation m). The units of angular measure are assumed to be in degrees. A description of each of the file formats are as follows:
  - 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
    ```

  - Polar. In this format, the three columns represent Measured Depth (MD), Inclination and Azimuth. Inclination is defined as; 0 degrees is vertical (downward pointing) and 90 degrees is horizontal. An angle greater than 90 degrees coincides with the term "drilling up". Azimuth is defined as; measuring clockwise 0 for a heading of North, 90 for a heading of East, 180 for a heading of South and 270 for a heading of West. 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
    ```

  - Single-point survey. This is a condensed version of the survey file consisting of just 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
```

- `uncased_radius` Radius of the open (uncased) hole. The `uncased_radius` parameter must always be supplied.

2.1.3 Procedure

The model is first initialized.

Initialize the model with basic quantities: system of measurement units, and input and output folder. The input folder must exist and be accessible. If the output folder does not exist it is 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 have then additional points inserted.

The drill string is read and initialized.

The drillstring 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 drillstring 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.

2.1.4 Example of specification

The following section describes a `setup` target for a partially cased hole.

```
[setup]
model_name = T+D Verification 2
input_folder = ./in
output_folder = ./out
drillstring_file = Well_2.csv
```

```
survey_listing = Survey_Listing_Well_2.csv
cased_length_fraction = 3150/4290
cased_radius = 0.22 [m]
uncased_radius = 0.28 [m]
max_element_length = 90 [ft]
```

2.1.5 Target depends on

The targets on which the present target depends:

- None.

2.1.6 Dependent targets

The targets that depend on this target:

- `selfweight`

2.1.7 Visualization targets

The applicable visualization targets:

- `show_borehole_profile`,
- `show_deflection_curve`,
- `show_internal_force`,
- `show_shape`,
- `show_shape_fly_through`.

2.2 Target `selfweight`

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

2.2.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[selfweight]
mass_density_of_drilling_fluid = 1500 [KG/M^3]
remark =
WOB = 0 [lbf]
```

2.2.2 Description of target data

- `mass_density_of_drilling_fluid` Mass density of the drilling fluid.
- `remark`
  A one line comment to describe the target (optional).
- `WOB` Weight-on-bit (WOB) force.

2.2.3 Procedure

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 tolerance

`Hook_force_tol=max([1e-3*WOB,1e-5*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 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 axial restraint to mimic rock-bit contact. Finally, at the top drive a hook force is applied in the direction tangential to the borehole curve of a magnitude that will produce 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.

2.2.4 Example of specification

This target specification is for a bit rotating off-bottom (WOB is zero).

```
[selfweight]
mass_density_of_drilling_fluid = 1380 [KG/M^3]
WOB = 0 [lbf]
```

2.2.5 Target depends on

The targets on which the present target depends:

- `setup`.

2.2.6 Dependent targets

The targets that depend on this target:

- `modal`.

2.2.7 Visualization targets

The applicable visualization targets:

- `show_deflection_curve`,
- `show_internal_force`,
- `show_shape`,
- `show_shape_fly_through`.

2.3 Target modal

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

2.3.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[modal]
dynamic_viscosity_of_drilling_fluid = 30*(1/100) [GM/CM/SEC]
remark =
```

2.3.2 Description of target data

- dynamic_viscosity_of_drilling_fluid Dynamic viscosity of the drilling fluid.
- remark A one line comment to describe the target (optional).

2.3.3 Procedure

The contact with the borehole is evaluated to find where to put 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 drillstring. Axial rotation is prevented at the rotary table and also at the bit.

2.3.4 Example of specification

This target specification is for a bit rotating in drilling mud.

```
[modal]
dynamic_viscosity_of_drilling_fluid = 30*(1/100) [GM/CM/SEC]
remark = Note:  we are assuming drilling mud is used
```

2.3.5 Target depends on

The targets on which the present target depends:

- selfweight.

2.3.6 Dependent targets

The targets that depend on this target:

- free_vibration,
- critical_rpm,
- lateral_map.

2.3.7 Visualization targets

The applicable visualization targets:

- None.

2.4 Target `free_vibration`

This target solves the free-vibration problem for the drill string under static loads and borehole constraint.

2.4.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[free_vibration]
number_of_modes = 5
remark =
```

2.4.2 Description of target data

- `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).

2.4.3 Procedure

The target solves the free-vibration problem. Note: one must be careful not to ask for too many natural frequencies: there is only as many as 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 the target modal.

2.4.4 Example of specification

This target specification is for a a free vibration analysis for 15 natural frequencies and the associated modes.

```
[free_vibration]
number_of_modes = 15
```

2.4.5 Target depends on

The targets on which the present target depends:

- `modal`.

2.4.6 Dependent targets

The targets that depend on this target:

- critical_rpm.

2.4.7 Visualization targets

The applicable visualization targets:

- show_frequencies,
- show_mode_shape.

2.5 Target critical_rpm

This target solves the critical-rpm problem for the drill string rotating at steady state with lateral eccentricity under static loads and borehole constraint.

2.5.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[critical_rpm]
eccentricity = 0.1 [in]
remark =
RPM_range = 0,100 [rpm]
RPM_step = 5 [rpm]
TOB = 0 [lbf*ft]]
WOB = 0 [lbf
```

2.5.2 Description of target data

- eccentricity Eccentricity of the axis about which the drill string rotates.
- remark A one line comment to describe the target (optional).
- RPM_range The rpm range.
- RPM_step Step to sample the rpm range.
- TOB Applied torque on bit.
- WOB Applied weight on bit.

2.5.3 Procedure

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 the target modal.

2.5.4 Example of specification

This target specification is for a critical-rpm analysis for non-zero weight on bit and torque on bit.

```
[critical_rpm]
eccentricity = 0.2 [in]
RPM_range = 0,400 [rpm]
RPM_step = 5 [rpm]
TOB = 500 [lbf*ft]
WOB = 5000 [lbf]
```

2.5.5 Target depends on

The targets on which the present target depends:

- `free_vibration`.

2.5.6 Dependent targets

The targets that depend on this target:

- None.

2.5.7 Visualization targets

The applicable visualization targets:

- `show_critical_rpm`.

2.6 Target `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.

2.6.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[lateral_map]
eccentricity = 0.1 [in]
remark =
RPM_range = 0,100 [rpm]
RPM_step = 5[rpm]
TOB = 0[lbf*ft]
WOB_range = 0,100 [kilo*lbf]
WOB_step = 5 [kilo*lbf]
```

2.6.2 Description of target data

- `eccentricity` Eccentricity of the axis about which the drill string rotates.
- `remark` A one line comment to describe the target (optional).
- `RPM_range` The rpm range.
- `RPM_step` Step to sample the rpm range.
- `TOB` Applied torque on bit.
- `WOB_range` Range of the applied weight on bit.
- `WOB_step` Step to sample the weight on bit range.

2.6.3 Procedure

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 the target `modal`.

2.6.4 Example of specification

This target specification is for a lateral-map analysis for non-zero torque on bit, the weight on bit 30, 35, 40, 45, 50 thousands of pounds, and 10, 20, 30, 40, 50 rpm.

```
[lateral_map]
  eccentricity = 0.1 [in]
  RPM_range = 10,50 [rpm]
  RPM_step = 10 [rpm]
  TOB = 500[lbf*ft]
  WOB_range = 30,50 [kilo*lbf]
  WOB_step = 5 [kilo*lbf]
```

2.6.5 Target depends on

The targets on which the present target depends:

- `free_vibration`.

2.6.6 Dependent targets

The targets that depend on this target:

- None.

2.6.7 Visualization targets

The applicable visualization targets:

- `show_lateral_map`.

2.7 Target `rotate`

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

2.7.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[rotate]
bottom_unevenness_amplitude = 0.0 [mm]
bottom_unevenness_angular_frequency = 3*2*pi
drilling_friction_coefficient_kinetic = []
confined_compressive_strength = 25000 [psi]
mass_density_of_drilling_fluid = 1500 [KG/M^3]
cutter_diameter = 19 [MM]
drilling_static_to_kinetic_friction_ratio = 1.25
max_friction_angular_velocity = 0.05 [RPM]
max_friction_sliding_velocity = 5 [mm/sec]
max_rpm = 200 [RPM]
min_steps_per_rev = 30
modal_damping = 0.02
modal_damping_frequencies = 0.1, 1.0 [Hz]
Rayleigh_damping_mass = 1e-4 [sec]
Rayleigh_damping_stiffness = 0. [sec^-1]
rotary_table_mass_moment_of_inertia = 0 [N*m*s^2/rad]
remark =
restart = 0
ROP_a1=3.429e-3 [m/s]
ROP_a2=5.672e-8 [m/s*N^-1]
ROP_a3=1.374e-4 [m/s*(rad/s)^-1]
save_as_restart = -1
tend = 1 [sec]
TOB_control_d = 0 [lbf*ft/(rpm/s)]
TOB_control_i = 0 [lbf*ft/(rpm*s)]
TOB_control_p = 0 [lbf*ft/rpm]
TOB_control_limit = [] [lbf*ft]
TOB_rpm_table = [] [rpm]
TOB_t_table = [] [s]
TOB_tob_table = [] [lbf*ft]
tstart = 0 [sec]
wall_friction_coefficient_kinetic = 0.3
wall_static_to_kinetic_friction_ratio = 1.25
WOB_t_table = [] [s]
WOB_wob_table = [] [lbf]
```

2.7.2 Description of target data

- `bottom_unevenness_amplitude` Amplitude of the bottom unevenness, which can generate oscillation in the WOB, with the angular frequency given by the parameter `bottom_unevenness_angular_frequency`.

- bottom_unevenness_angular_frequency Angular frequency of the bottom unevenness. For the tri-cone bit this will be $3 \times 2\pi$.
- drilling_friction_coefficient_kinetic Kinetic drilling friction torque coefficient, dimensionless. By default, the drilling friction torques coefficient is not given (the value is []). There are two ways of setting the coefficient: either by specifying its value in the INI file, or by using a prediction of the coefficient from confined compressive strength of the rock on the bottom. For the prediction the parameters confined_compressive_strength, mass_density_of_drilling_fluid, and cutter_diameter are used. For direct specification of the drilling friction torque coefficient these parameters are not needed and they are not used.
- confined_compressive_strength Confined compressive strength of the rock. This parameter is not used if the drilling friction torque coefficient is supplied as input.
- mass_density_of_drilling_fluid Mass density of the drilling fluid (mud). 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.
- drilling_static_to_kinetic_friction_ratio Ratio of static to kinetic drilling friction torque coefficient. The drilling torque is produced as a product of the WOB, the bit radius, and this coefficient:

```
Frictional Torque = mu(A) * WOB * (2/3) * bit_radius
```

  Here A is the relative angular sliding velocity and mu(A) is the velocity-dependent drilling coefficient.
- max_friction_angular_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 has a maximum for very small angular velocities. This coefficient applies to the dynamic friction at the bit.
- max_friction_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 has 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.
- max_rpm Estimate of the fastest rpm at which the drill string is going to rotate. This parameter is not constrain the actual motion of the bit, only the maximum allowable time step.
- min_steps_per_rev The smallest number of steps to take per revolution of the bit. This in conjunction with max_rpm determines the maximum time step that the integrator is allowed to take.
- 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 drillstring. 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. The Rayleigh damping is either specified with modal_damping, or directly by supplying Rayleigh_damping_mass and Rayleigh_damping_stiffness.
- 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 drillstring in torsion. The Rayleigh damping assumes a minimum somewhere between the modal damping frequencies. These frequencies are only used when `modal_damping` is specified.

- `Rayleigh_damping_mass` Coefficient of mass-proportional damping; it can be supplied instead of the modal damping coefficient (together with the stiffness-proportional damping coefficient). This coefficient is ignored when the modal damping coefficient is supplied.
- `Rayleigh_damping_stiffness` Coefficient of stiffness-proportional damping; it can be supplied instead of the modal damping coefficient (together with the mass-proportional damping coefficient). This coefficient is ignored when the modal damping coefficient is supplied.
- `rotary_table_mass_moment_of_inertia` Mass moment of inertia of the rotary table.
- `remark` A one line comment to describe the target (optional).
- `restart` Load the restart data numbered `restart`. Specifying `restart = 0` means start from scratch; `restart` as a positive integer is the number of restart from which to resume the computation.
- `ROP_a1` Parameter of the ROP (rate of penetration) model. This is the constant term.
- `ROP_a2` Parameter of the ROP (rate of penetration) model. This is the proportionality coefficient of the WOB contribution to the ROP.
- `ROP_a3` Parameter of the ROP (rate of penetration) model. This is the proportionality coefficient of the angular speed contribution to the ROP.
- `save_as_restart` Save the computed data as this restart number; if this is supplied as less than zero, it is assumed that `save_as_restart=restart+1`.
- `tend` Time at which the direct time stepping ends.
- `TOB_control_d` Derivative-control parameter of the PID (Proportional, Integral, Derivative) controller of the torque of the rotary table.
- `TOB_control_i` Integral-control parameter of the PID (Proportional, Integral, Derivative) controller of the torque of the rotary table.
- `TOB_control_p` Proportional-control parameter of the PID (Proportional, Integral, Derivative) controller of the torque of the rotary table.
- `TOB_control_limit` Limit on the torque that can be exerted by the rotary table.
- `TOB_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. Call for the example below.
- `TOB_t_table` Array of times at which TOB (or rather the torque at the rotary table) values or the desired RPM values are given.
- `TOB_tob_table` Array of TOB (or rather of the torque at the rotary table) values.
- `tstart` Time at which the direct time stepping starts.
- `cased_wall_friction_coefficient_kinetic` Kinetic coefficient of friction at the surface of a cased portion of the borehole.
- `cased_wall_static_to_kinetic_friction_ratio` Ratio of static the kinetic friction at the surface of the cased portion of the borehole.
- `uncased_friction_coefficient_kinetic` Kinetic coefficient of friction at the surface of a uncased portion of the borehole.
- `uncased_wall_static_to_kinetic_friction_ratio` Ratio of static the kinetic friction at the surface of the uncased portion of the borehole.
- `WOB_t_table` Array of times at which WOB values are given.
- `WOB_wob_table` Array of corresponding WOB values. The current WOB is obtained by interpolating from the tables `WOB_t_table` and `WOB_wob_table`.

2.7.3 Procedure

Control of drilling parameters

The torque on bit can be controlled either by prescribing a table of time-TOB pairs or by prescribing RPM at the rotary table by giving the table of time-rpm pairs. So either the user needs

to specify the two parameters TOB_t_table, TOB_tob_table, or the two parameters TOB_t_table, TOB_rpm_table. Either TOB_tob_table, is supplied as empty array ([]), or TOB_rpm_table needs to be supplied as empty array: both cannot be defined non-empty at the same time.

When the RPM table is specified, the torque-on-bit control function creates a PID controller with constants given by these three parameters: TOB_control_d, TOB_control_i, TOB_control_p.

The weight-on-bit is controlled by prescribing a table of time-WOB pairs, WOB_t_table and WOB_wob_table.

Boundary conditions

The boundary conditions are as follows: At the top drive we apply spring restraints against lateral displacements and the rotations except for the axial one are also penalized by spring constants. At the bit we apply unilateral axial restraint to mimic rock-bit contact. Finally, at the top drive a hook force is applied in the direction tangential to the borehole curve of a magnitude that will produce 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: for a given value of the dynamic WOB we calculate the corresponding hook force 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 the magnitude of the iterative correction to the displacements. When convergence cannot be achieved with current time step, the time step is reduced and the iteration is re-tried. Conversely, if iteration was brief and successful an attempt is made to increase the time step length, up to the limit determined by the minimum number of time steps to take per revolution.

Rate of Penetration (ROP) model

The ROP model is based on the following formulas:

```
ROP = -ROP_a1 + (WOB>0)*ROP_a2*WOB + (Omega_bit>0)*ROP_a3*Omega_bit;
ROP = ROP * (Omega_bit > max_friction_angular_velocity);
```

First, the ROP is evaluated from the formula

```
ROP = -ROP_a1 + (WOB>0)*ROP_a2*WOB + (Omega_bit>0)*ROP_a3*Omega_bit;
```

where ROP_a1, ROP_a2, and ROP_a3 are parameters of the model, WOB is the weight on bit force, and 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 so that the teeth are cutting, that is for the bit rotating with an angular velocity greater than the maximum friction angular velocity. Below this velocity the bit is assumed to be stuck.

```
ROP = ROP * (Omega_bit > max_friction_angular_velocity);
```

2.7.4 Example of specification

Control of RPM

TOB applied with a Proportional-Integral (PI) controller (the derivative control parameter is zero by default). The desired RPM is 60 between 0.0 seconds and 50.0 seconds, which is then ramped up to 120 rpm between 50.0 and 70.0 seconds, and then the desired RPM is 120.

```
[rotate]
drilling_friction_coefficient_kinetic = 0.4519
drilling_static_to_kinetic_friction_ratio = 1.25
max_friction_angular_velocity = 0.5 [RPM]
max_friction_sliding_velocity = 50 [mm/sec]
max_rpm = 60 [RPM]
modal_damping = 0.02
modal_damping_frequencies = 0.1, 1.0 [Hz]
restart = 0
save_as_restart = 4
tstart = 0 [sec]
tend = 200 [sec]
TOB_control_i = 200 [lbf*ft/(rpm*s)]
TOB_control_p = 10 [lbf*ft/rpm]
TOB_rpm_table = [60,60,120,120] [rpm]
TOB_t_table = [0,50,70,200] [s]
uncased_wall_friction_coefficient_kinetic = 0.3
uncased_wall_static_to_kinetic_friction_ratio = 1.25
WOB_t_table = [ 0] [s]
WOB_wob_table = [5000] [lbf]
```

2.7.5 Target depends on

The targets on which the present target depends:

- `selfweight`.

2.7.6 Dependent targets

The targets that depend on this target:

- None.

2.7.7 Visualization targets

The applicable visualization targets:

- `show_deflection_curve`,
- `show_internal_force`,
- `show_shape`,
- `show_shape_fly_through`.

2.8 Target `rotate_cat`

This target concatenates results from separate sequential rotate simulation restarts.

2.8.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[rotate_cat]
remark =
restart_list = 0
save_as_restart = -1
```

2.8.2 Description of target data

- `remark` A one line comment to describe the target (optional).
- `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 `rotate` targets must be contiguous in time and they must be listed in the order in which the time increases. See the example below.
- `save_as_restart` Save the computed data as this restart number. This number cannot be inferred, it must be supplied.

2.8.3 Procedure

This target concatenates the result data sets from a series of previously calculated restarts into a single data set that can be referred to as yet another restart.

2.8.4 Example of specification

As an example, consider the following scenario: the `rotate` target was run four times, once starting from restart 0 to simulate the rotating of the drillstring from 0.0 seconds to 5.0 seconds, which was saved as restart 1, once to simulate the rotating from 5.0 seconds to 60 seconds, which was saved as restart 2, once for rotating from 60 seconds to 120 seconds, which was saved as restart 3, and finally for 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.

```
[rotate_cat]
remark = Do not consider the restart 3, replace it with 4
restart_list = 1,2,4
save_as_restart = 5
```

Note that restart 5 produced in this way is in effect completely equivalent to simulating the rotating of the drillstring (under the same conditions under which the drillstring was moving for the restarts 1,2,4) 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 drillstring was moving must consist of contiguous, non-overlapping, sub-intervals, in this case 0-5, 5-60, and 60-120 seconds.

2.8.5 Target depends on

The targets on which the present target depends:

- `rotate`.

2.8.6 Dependent targets

The targets that depend on this target:

- None.

2.8.7 Visualization targets

The applicable visualization targets:

- `show_deflection_curve`,
- `show_internal_force`,
- `show_shape`,
- `show_shape_fly_through`.

3

Visualization targets

3.1 Target `show_borehole_profile`

3.1.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_borehole_profile]
image_dpi = 96
image_height = 936
image_name = borehole_profile.jpg
image_width = 615
interactive = false
length_units = ft
remark =
```

3.1.2 Description of target data

- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the horizontal axis.
- `remark` A one line comment to describe the target (optional).

3.1.3 Procedure

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

Note that the interactive plot can be manipulated using the 3-D visualization tool described in the appendix.

3.1.4 Example of specification

```
[show_borehole_profile]
image_name = borehole_profile.jpg
length_units = ft
remark = Note the two straight sections: the vertical and the sail
```

3.1.5 Target depends on

The targets on which the present target depends:

- `setup`.

3.1.6 Dependent targets

The targets that depend on this target:

- None.

3.2 Target `show_internal_force`

3.2.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_internal_force]
image_dpi = 96
image_height = 936
image_name = internal_force.jpg
image_width = 615
interactive = false
length_units = ft
remark =
resultant = N
resultant_units = lbf
style = r.-
target = setup
xlim = 0,1
```

3.2.2 Description of target data

- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.

- length_units Measurement units for the horizontal axis.
- remark A one line comment to describe the target (optional).
- resultant A list of codes of the resultants to plot. 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), Mmax (maximum bending moment). The input resultant 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). Note that resultants of different meanings (such as forces with torques) should not be mixed together in a single graph.
- style List of style strings to be used for the colors and markers of the locations on the list distance_from_bit.
- target Name of target for which the internal force should be displayed.
- xlim This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.

3.2.3 Procedure

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

3.2.4 Example of specification

Display the internal axial force in the drillstring due to the deformation of the drillstring under self-weight loads.

```
[show_internal_force]
image_name = selfweight_internal_force_Axial.jpg
length_units = ft
resultant = N
resultant_units = kilo*lbf
target = selfweight
style = k-. k-- r.-
```

3.2.5 Target depends on

The targets on which the present target depends:

- setup, selfweight.

3.2.6 Dependent targets

The targets that depend on this target:

- None.

3.3 Target show_contact_forces

Produce a plot of the contact forces between the drill string and the borehole.

3.3.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_contact_forces]
force_scale=100 [ft/lbf]
image_dpi = 96
image_height = 936
image_name = shape.jpg
image_width = 615
interactive = false
length_units = ft
remark =
target = selfweight
```

3.3.2 Description of target data

- `force_scale` Numerical factor to scale the length of forces compared to the dimensions of the drill string.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `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).

3.3.3 Procedure

The plot shows 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 specified as input. Any target that computes the deformed shape of the drill string is allowed.

Note that the interactive plot can be manipulated using the 3-D visualization tool described in the appendix.

3.3.4 Example of specification

The following specification is for a plot of the contact forces that maintain the drill string within the borehole, without any loads, due purely to the curvature of the borehole (i. e. for the target `setup`).

```
[show_contact_forces]
force_scale=1000 [ft/lbf]
image_name = setup_shape.jpg
target = setup
```

3.3.5 Target depends on

The targets on which the present target depends:

- Any target that computes the deformed shape of the drill string.

3.3.6 Dependent targets

The targets that depend on this target:

- None.

3.4 Target show_critical_rpm

Produce a plot of the lateral deflection of the drill string under eccentric steady-state rotation conditions.

3.4.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_critical_rpm]
deflection_units = in
image_dpi = 96
image_height = 936
image_name = critical_rpm.jpg
image_width = 615
interactive = false
remark =
xlim = 0,1
```

3.4.2 Description of target data

- `deflection_units` Measurement units for the deflections. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.

- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the rpm axis to be shown in the plot.
- `remark` A one line comment to describe the target (optional).

3.4.3 Procedure

The plot shows 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 the CSV format.

3.4.4 Example of specification

The following specification is for a plot of the middle third of the rpm range.

```
[show_critical_rpm]
  image_name = critical_rpm.jpg
  xlim = 1/3 2/3
```

3.4.5 Target depends on

The targets on which the present target depends:

- `critical_rpm`.

3.4.6 Dependent targets

The targets that depend on this target:

- None.

3.5 Target `show_deflection_curve`

Produce a plot of the schematic deflection curve of the drillstring.

3.5.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
  [show_deflection_curve]
  deflection_units = in
  image_dpi = 96
  image_height = 936
  image_name = deflection_curve.jpg
  image_width = 615
  interactive = false
  length_units = ft
  remark =
  target = setup
  xlim = 0,1
```

3.5.2 Description of target data

- `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.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `target` Name of the target for which deflection curve should be plotted. Any target which computes the deformed shape of the drillstring can be specified.
- `remark` A one line comment to describe the target (optional).

3.5.3 Procedure

The plot shows the deflection curve of the drillstring. 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 is going to 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 the CSV format.

3.5.4 Example of specification

The following specification is for a plot of the deflection curve of the drillstring under self-weight loads.

```
[show_deflection_curve]
deflection_units = in
image_name = deflection_curve.jpg
length_units = ft
target = selfweight
```

3.5.5 Target depends on

The targets on which the present target depends:

- Any target that computes the deformed shape of the drillstring.

3.5.6 Dependent targets

The targets that depend on this target:

- None.

3.6 Target `show_frequencies`

Produce a plot of the free-vibration (natural) frequencies.

3.6.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_frequencies]
image_dpi = 96
image_height = 936
image_name = frequencies.jpg
image_width = 615
interactive = false
remark =
xlim = 0,1
```

3.6.2 Description of target data

- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `remark` A one line comment to describe the target (optional).

3.6.3 Procedure

The plot shows the free-vibration frequencies in a graph. 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 the CSV format.

3.6.4 Example of specification

The following specification is for a plot of the first 50% of the calculated natural frequencies.

```
[show_frequencies]
  image_name = frequencies.jpg
  xlim = 0,1/2
```

3.6.5 Target depends on

The targets on which the present target depends:

- free_vibration.

3.6.6 Dependent targets

The targets that depend on this target:

- None.

3.7 Target show_lateral_map

Produce a 3-D surface plot of the lateral deflection of the drill string under eccentric steady-state rotation conditions.

3.7.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_lateral_map]
deflection_units = in
force_units = kilo*lbf
image_dpi = 96
image_height = 936
image_name = lateral_map.jpg
image_width = 615
interactive = false
remark =
```

3.7.2 Description of target data

- deflection_units Measurement units for the deflections. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- force_units Measurement units for the WOB forces. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- image_dpi Dots-per-inch resolution of the image.
- image_height Image height in paper units (points).
- image_name Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- image_width Image width in paper units (points).
- interactive Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- remark A one line comment to describe the target (optional).

3.7.3 Procedure

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.

3.7.4 Example of specification

The following specification is for a plot of the lateral map using millimeters for the deflections and kiloNewton for the forces.

```
[show_lateral_map]
 deflection_units = mm
 force_units = kilo*N
 image_name = lateral_map.jpg
```

3.7.5 Target depends on

The targets on which the present target depends:

- `lateral_map`.

3.7.6 Dependent targets

The targets that depend on this target:

- None.

3.8 Target `show_mode_shape`

Produce a plot of the free-vibration mode shape.

3.8.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_mode_shape]
drillstring_length_fraction=0.1
image_dpi = 96
image_height = 936
image_name = mode_shape.jpg
image_width = 615
interactive = false
length_units = ft
mode_number = 1
remark =
show_local_coords=false
```

3.8.2 Description of target data

- `drillstring_length_fraction` The magnitude of the mode shape is selected to make the largest amplitude of lateral motion this fraction of the total drillstring length. This should be a small fraction.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).

- image_name Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- image_width Image width in paper units (points).
- interactive Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- length_units Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- mode_number Number of mode shape 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).
- 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.

3.8.3 Procedure

The plot shows the free-vibration mode shape. The boundary conditions are as specified for the target free_vibration.

Note that the interactive plot can be manipulated using the 3-D visualization tool described in the appendix.

3.8.4 Example of specification

The following specification is for a plot of the first mode shape.

```
[show_mode_shape]
 mode_number = 1
 image_name = mode_shape_1.jpg
```

3.8.5 Target depends on

The targets on which the present target depends:

- free_vibration.

3.8.6 Dependent targets

The targets that depend on this target:

- None.

3.9 Target show_rotate_axial_displacement

Produce a plot of the axial displacements of various locations on the drill string during rotating.

3.9.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_axial_displacement]
distance_from_bit = 0,1
image_dpi = 96
image_height = 936
image_name = rotate_axial_displacement.jpg
image_width = 615
interactive = false
length_units = in
      output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.9.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the axial displacement should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.9.3 Procedure

The plot shows the axial displacements at selected locations along the drillstring as functions of time. The axial displacements are measured along the tangent vectors to the drillstring midline.

Positive displacement is measured when it occurs in the direction from the bit towards the rotary table.

The axial displacement at relative distance from the bit $0 \leq x \leq 1$ 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 the CSV format.

3.9.4 Example of specification

The following specification is for a plot of the axial displacement (`distance_from_bit`=0) at the bit and at the top drive (`distance_from_bit`=1). The data should be produced for restart 14.

```
[show_rotate_axial_displacement]
distance_from_bit =  0,1
image_name = rotate_14_axial_displacement.jpg
length_units = in
restart = 14
style = r.-,g--
time_units = sec
```

3.9.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.9.6 Dependent targets

The targets that depend on this target:

- None.

3.10 Target `show_rotate_rpm`

Produce a plot of the axial angular velocity in RPM of various locations on the drill string during rotating.

3.10.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_rpm]
distance_from_bit = 0,1
image_dpi = 96
image_height = 936
image_name = rotate_rpm.jpg
image_width = 615
interactive = false
length_units = in
output_sampling_step = 0.05 [sec]
```

```
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.10.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the angular velocity should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.10.3 Procedure

The plot shows the RPM axial velocity of the rotating drillstring in a graph.

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

3.10.4 Example of specification

The following specification is for a plot of the axial angular velocity in RPM (`distance_from_bit`=0) at the bit and at the top drive (`distance_from_bit`=1). The data should be produced for restart 14.

```
[show_rotate_rpm]
distance_from_bit =  0,1
image_name = rotate_14_rpm.jpg
length_units = in
restart = 14
style = r.-,g--
time_units = sec
```

3.10.5 Target depends on

The targets on which the present target depends:

- rotate.

3.10.6 Dependent targets

The targets that depend on this target:

- None.

3.11 Target show_rotate_tob

Produce a plot of the torques at the bit and at the top drive during rotating.

3.11.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_tob]
image_dpi = 96
image_height = 936
image_name = rotate_tob.jpg
image_width = 615
interactive = false
output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
torque_units = lbf*ft
```

3.11.2 Description of target data

- image_dpi Dots-per-inch resolution of the image.
- image_height Image height in paper units (points).
- image_name Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- image_width Image width in paper units (points).
- interactive Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- output_sampling_step If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- remark A one line comment to describe the target (optional).
- xlim This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.

- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.
- `torque_units` Measurement units for the torques. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.

3.11.3 Procedure

The plot shows the actual torque at the bit and the applied torque at the top drive during the rotating of the drillstring in a graph.

3.11.4 Example of specification

The following specification is for a plot of the torques at the bit and at the top drive. The data should be produced for restart 14.

```
[show_rotate_tob]
image_name = rotate_14_tob.jpg
length_units = in
restart = 14
style = r.-,g--
torque_units = kilo*lbf*ft
```

3.11.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.11.6 Dependent targets

The targets that depend on this target:

- None.

3.12 Target `show_rotate_lateral_displacement`

Produce a plot of the lateral displacements of various locations on the drill string during rotating as a function of time.

3.12.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_lateral_displacement]
distance_from_bit = 0, 1
image_dpi = 96
image_height = 936
```

```
image_name = rotate_lateral_displacement.jpg
image_width = 615
interactive = false
length_units = in
output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.12.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the lateral displacement should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.12.3 Procedure

The plot shows the lateral displacements of the centroid of the drillstring as functions 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 drillstring 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 drillstring 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 on the basis vectors `h` and `v`. Note that when the transverse displacements are plotted at several locations along the drillstring, each of the locations will have its own local coordinate system defined as described above.

The lateral displacements at relative distance from the bit $0 \leq x \leq 1$ are shown in the legend of the plot as u_h@d=x (component on the basis vector `h`) and u_v@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 the CSV format.

3.12.4 Example of specification

The following specification is for a plot of the lateral displacement (`distance_from_bit`=0) at the bit and at the top drive (`distance_from_bit`=1). The data should be produced for restart 14.

```
[show_rotate_lateral_displacement]
distance_from_bit =  0,1
image_name = rotate_14_lateral_displacement.jpg
length_units = in
restart = 14
style = r.-,g--
time_units = sec
```

3.12.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.12.6 Dependent targets

The targets that depend on this target:

- None.

3.13 Target `show_rotate_lateral_displacement_orbit`

Produce a plot of the lateral displacements of various locations on the drill string during rotating as a function of time.

3.13.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_lateral_displacement_orbit]
distance_from_bit = 0, 1
image_dpi = 96
image_height = 936
image_name = rotate_lateral_displacement_orbit.jpg
image_width = 615
interactive = false
```

```
length_units = in
output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
xlim = 0,1
```

3.13.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the lateral displacement should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `length_units` Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the time axis to be shown in the plot. Note that the time axis is implicit in this plot: the time interval selects the displacements to plot in the orbit.

3.13.3 Procedure

The plot shows the orbit plot of the lateral displacements of the centroid of the drillstring. 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 relative distance from the bit $0 \leq x \leq 1$ 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 the CSV format.

3.13.4 Example of specification

The following specification is for an orbit plot of the lateral displacement (`distance_from_bit`=0) at the bit and at the top drive (`distance_from_bit`=1). The data should be produced for restart 14.

```
[show_rotate_lateral_displacement_orbit]
distance_from_bit =  0,1
image_name = rotate_14_lateral_displacement_orbit.jpg
length_units = in
restart = 14
style = r.-,g--
time_units = sec
```

3.13.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.13.6 Dependent targets

The targets that depend on this target:

- None.

3.14 Target `show_rotate_vibration_risk_index`

Produce a plot of the vibration risk index during rotating.

3.14.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_vibration_risk_index]
image_dpi = 96
image_height = 936
image_name = rotate_vibration_risk_index.jpg
image_width = 615
interactive = false
length_units = in
output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.14.2 Description of target data

- image_dpi Dots-per-inch resolution of the image.
- image_height Image height in paper units (points).
- image_name Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- image_width Image width in paper units (points).
- interactive Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- length_units Measurement units for the lengths. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- remark A one line comment to describe the target (optional).
- xlim This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- output_sampling_step If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- restart Load the restart data of the rotate target for the restart number restart. The restart number is in general > 0; and error results if restart that does not exist is specified.
- style List of style strings to be used for the colors and markers of the locations on the list distance_from_bit.
- time_units Measurement units for the time axis.

3.14.3 Procedure

The plot shows vibration risk index evolution during the rotating of the drillstring in a graph.

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

3.14.4 Example of specification

The following specification is for a plot of the vibration risk index for restart 14.

```
[show_rotate_vibration_risk_index]
image_name = rotate_14_vibration_risk_index.jpg
length_units = in
restart = 14
style = r.-,g--
time_units = min
```

3.14.5 Target depends on

The targets on which the present target depends:

- rotate.

3.14.6 Dependent targets

The targets that depend on this target:

- None.

3.15 Target `show_rotate_wob`

Produce a plot of the weight on bit (WOB) forces, both desired WOB and the bit actually computed at the bit during rotating.

3.15.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_wob]
image_dpi = 96
image_height = 936
image_name = rotate_wob.jpg
image_width = 615
interactive = false
force_units = lbf
output_sampling_step = 0.05 [sec]
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.15.2 Description of target data

- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `force_units` Measurement units for the forces. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance\string_from\string_bit`.
- `time_units` Measurement units for the time axis.

3.15.3 Procedure

The plot shows the actual WOB at the bit and the desired WOB during the rotating of the drillstring in a graph.

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

3.15.4 Example of specification

The following specification is for a plot of the desired WOB and the WOB actually computed at the bit. The data should be produced for restart 14.

```
[show_rotate_wob]
image_name = rotate_14_wob.jpg
length_units = in
restart = 14
style = r.-,g--
force_units = kilo*lbf
```

3.15.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.15.6 Dependent targets

The targets that depend on this target:

- None.

3.16 Target `show_rotate_whirl_speed`

Produce a plot of the whirling speeds of various locations on the drill string during rotating as a function of time.

3.16.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_whirl_speed]
distance_from_bit = 0, 1
image_dpi = 96
image_height = 936
image_name = show_rotate_whirl_speed.jpg
image_width = 615
interactive = false
output_sampling_step = 0.05 [sec]
remark =
restart = 1
rotation_speed_units = rpm
style = r.-,g--
time_units = sec
```

3.16.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the lateral displacement should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `remark` A one line comment to describe the target (optional).
- `rotation_speed_units` Measurement units for the rotation speeds. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.16.3 Procedure

The plot shows the whirling speeds of the drillstring as functions of time. Both the axial angular velocity (speed) of the rotating drillstring (marked with symbol ω_a) and the angular velocity with which the centroid of the drillstring rotates about the center of the borehole (designated as the *whirling speed*, marked with symbol ω) are shown. The rotation speeds are measured in a 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 drillstring is positive, and the whirling speed of the centroid is negative, the motion of the drillstring corresponds to backward whirl. Conversely, if both rotation speeds have the same sign, the motion of the centroid of the drillstring is forward whirl.

The axial angular velocity at relative distance from the bit $0 \leq x \leq 1$ is shown in the legend of the plot as ω_a@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 the CSV format.

3.16.4 Example of specification

The following specification is for a plot of the whirling speeds at the distance `distance_from_bit`=0 (at the bit) and at the stabilizer which in this case is assumed to be located at one quarter of the drillstring length (`distance_from_bit`=0.25). The data should be produced for restart 14.

```
[show_rotate_whirl_speed]
distance_from_bit =  0, 0.25
```

```
image_name = rotate_14_whirl_speed.jpg
rotation_speed_units = rpm
restart = 14
style = r.-,g--
time_units = sec
```

3.16.5 Target depends on

The targets on which the present target depends:

- rotate.

3.16.6 Dependent targets

The targets that depend on this target:

- None.

3.17 Target show_rotate_accelerometer

Produce a plot of the simulated accelerometer reading at various locations on the drill string during rotating as a function of time.

3.17.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_accelerometer]
acceleration_units = m/sec^2
distance_from_bit = 0
image_dpi = 96
image_height = 936
image_name = rotate_accelerometer.jpg
image_width = 615
interactive = false
orientation_angle = 0 [deg]
output_sampling_step = 0.05 [sec]
position_angle = 0 [deg]
position_radius = 1/6 [ft]
remark =
restart = 1
style = r.-,g--
time_units = sec
```

3.17.2 Description of target data

- acceleration_units Measurement units for the accelerations. Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- distance_from_bit List of normalized distances from the bit of the locations at which the lateral displacement should be plotted.

- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `orientation_angle` An array of orientation angles, one for each accelerometer. The angle is between the radial line connecting the accelerometer with the centroid of the drillstring cross-section. Angle of 0^o means the accelerometer is oriented radially, angle of 90^o means the accelerometer is oriented circumferentially.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `position_angle` An array of position angles, one for each accelerometer. The angle is between the radial line arbitrarily taken along the local `h` axis and the radial line that connects the accelerometer with the centroid of the drillstring cross-section. The array of position angles `[0,120,240] [deg]` corresponds to the triple of accelerometers uniformly distributed around the circle.
- `position_radius` Radius at which the accelerometer is positioned (i.e. distance from the centroid of the cross-section).
- `remark` A one line comment to describe the target (optional).
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.17.3 Procedure

The plot shows the accelerometer readings as functions of time. The accelerations are are measured in the direction in which the accelerometer is installed. The position of the accelerometer is described with 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 the CSV format.

3.17.4 Example of specification

The following specification is for a plot of the accelerometer array located at three quarters of the length of the drillstring. There are three accelerometers, all three oriented radially (orientation angle is zero), they are uniformly distributed around the circumference at the same distance of 0.05 m. The data should be produced for restart 1000.

```
[show_rotate_accelerometer]
distance_from_bit = 0.75
image_name = rotate_1000_ACCELEROMETERS.jpg
interactive = true
```

```
orientation_angle = [0,0,0] [deg]
position_angle = [0,120,240] [deg]
position_radius = [0.05,0.05,0.05] [m]
restart = 1000
time_units = sec
xlim = 0,1
```

3.17.5 Target depends on

The targets on which the present target depends:

- rotate.

3.17.6 Dependent targets

The targets that depend on this target:

- None.

3.18 Target show_rotate_rop

Produce a plot of the rate of penetration (ROP) reading at various locations on the drill string during rotating as a function of time.

3.18.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_rop]
image_dpi = 96
image_height = 936
image_name = rotate_rop.jpg
image_width = 615
interactive = false
output_sampling_step = 0.05 [sec]
remark =
restart = 1
rop_units = in/sec
style = r.-,g--
time_units = sec
```

3.18.2 Description of target data

- image_dpi Dots-per-inch resolution of the image.
- image_height Image height in paper units (points).
- image_name Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- image_width Image width in paper units (points).

- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `output_sampling_step` If this parameter is set, the output is resampled with this step. This step could be longer than that used in the simulation, or it could be shorter. When it is longer, some of the detail from the simulation may be lost; when it is shorter, linear interpolation of the actually calculated data points is applied.
- `remark` A one line comment to describe the target (optional).
- `rop_units` Measurement units for the rate of penetration (ROP). Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `time_units` Measurement units for the time axis.

3.18.3 Procedure

The plot shows the rate of penetration (ROP) 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 the CSV format.

3.18.4 Example of specification

The following specification is for a plot of the ROP in meters per hour. The data should be produced for restart 1000.

```
[show_rotate_rop]
Image_height =  600
image_name =  rotate_rop.jpg
Image_width =  800
interactive =  true
restart =  1000
rop_units =  m/hr
style =  r.-,g--
time_units =  sec
xlim =  0.,1
```

3.18.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.18.6 Dependent targets

The targets that depend on this target:

- None.

3.19 Target show_rotate_whirl_indicator

Produce a plot of the whirl indicator at various locations on the drill string during rotating as a function of time.

3.19.1 List of target data

The target is defined by data in the INI file as shown below (default values including the applicable measurement units are indicated):

```
[show_rotate_whirl_indicator]
distance_from_bit=0,1
image_dpi = 96
image_height = 936
image_name = rotate_wi.jpg
image_width = 615
interactive = false
remark =
restart = 1
rotation_speed_units = rpm
style = r.-,g--
threshold_amplitude_ratio=0.99
time_units = sec
```

3.19.2 Description of target data

- `distance_from_bit` List of normalized distances from the bit of the locations at which the lateral displacement should be plotted.
- `image_dpi` Dots-per-inch resolution of the image.
- `image_height` Image height in paper units (points).
- `image_name` Image name (with or without an extension). The image is saved in the model folder. Extensions (formats) recognized: .tif, .tiff, .jpg, .png.
- `image_width` Image width in paper units (points).
- `interactive` Should the figure be displayed interactively? True or false. If interactive==true, the plots produced by the target are displayed on the screen and are available for interactive manipulation by the user. Otherwise the plots are produced automatically and stored in the model folder.
- `remark` A one line comment to describe the target (optional).
- `rotation_speed_units` Measurement units for the rate of rotation (rotation speed). Note that the units are not enclosed in square brackets as is required when supplying numerical values to target data.
- `xlim` This is a pair of numbers between zero and one, which is the normalized interval on the mode number axis to be shown in the plot.
- `restart` Load the restart data of the `rotate` target for the restart number `restart`. The restart number is in general > 0; and error results if restart that does not exist is specified.
- `style` List of style strings to be used for the colors and markers of the locations on the list `distance_from_bit`.
- `threshold_amplitude_ratio` Whirling indicator makes most sense when the drillstring is in contact with borehole or if the drillstring moves almost in contact with the borehole. Therefore, we define the whirling indicator to the displayed only if the fraction of the radius at which the drillstring center moves to the maximum radius (which defines contact of the drawstring with the borehole) is greater than the threshold ratio. Threshold ratio of 1.0 would mean that the

whirling indicator should only be shown for actual contact. Threshold ratio of 0.99 will request the whirling indicator to be shown whenever the drillstring is within 1 % of the maximum radius that it can displace before contacting the borehole surface.

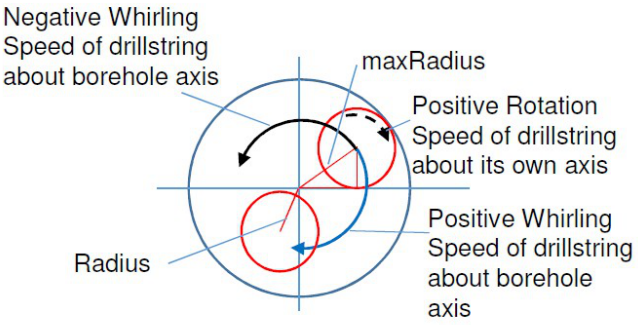
- `time_units` Measurement units for the time axis.

3.19.3 Procedure

The plot shows the whirling indicator as a function of time. The whirling indicator `WI` is defined as

$$WI = \frac{\texttt{omega}}{\texttt{omega\_a}} \times \frac{\texttt{Radius}}{\texttt{maxRadius}}$$

where `omega` is the angular velocity of the center of the drillstring as it moves about the center of the borehole, `omega_a` is the axial angular velocity of the drillstring about its own axis, `Radius` is the distance of the drillstring center from the center of the borehole, and `maxRadius` is the radius of the motion of the drillstring at which it contacts the borehole. Refer also to the sketch



The whirling indicator of magnitude at or above 1.0 (positive or negative) indicates whirling is established. `WI` positive indicates forward whirling, whereas `WI` negative indicates backward whirling.

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

3.19.4 Example of specification

The following specification is for a plot of the whirling indicator in rpm. The data should be produced for restart 1000. The whirling data should be shown at the midpoint of the drillstring (0.5) and at the bit (0.0).

```
[show_rotate_whirl_indicator]
distance_from_bit=0.5,0.0
restart = 1000
rotation_speed_units = rpm
threshold_amplitude_ratio=0.99
time_units = sec
```

3.19.5 Target depends on

The targets on which the present target depends:

- `rotate`.

3.19.6 Dependent targets

The targets that depend on this target:

- None.

4

Appendices

3-D visualization tool

Manipulation of the 3-D view: Switch to an appropriate mode as explained below, and modify the camera settings. Double click with the left mouse button to restore the original view.

In order to switch the camera manipulation mode one can use one of two methods. Either click with the right mouse button anywhere outside of the displayed graphics to get a context menu. Or, the controls are available by pressing keys when the mouse pointer is located within the general bounds of the plot:

- hit "z" key to switch to ZOOM mode,
- hit "r" key to switch to ROTATION mode,
- hit "d" key to switch to DOLLY mode (sideways translation),
- hit "t" key to switch to TARGET mode(setting of the camera target).

Note that the mode is indicated by the shape of the pointer. ZOOM  , ROTATION  , DOLLY  , TARGET .

- **In ROTATION mode:** Press and hold left mouse button to rotate about screen xy axis. Press and hold middle mouse button to rotate about screen z axis. Press '-' to slow down rotation, press '+' to speed up rotation.
- **In ZOOM mode:** Press and hold left mouse button to zoom in and out.
- **In DOLLY mode:** press and hold left mouse button to dolly the camera horizontally and vertically.
- **In TARGET mode:** Click on the point to which the camera should be targeted. For the drillstring they are typically the joints between the components, or the joints between finite elements. For the borehole they are the control points of the midline curve.

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