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Open Source Drilling Project

Mechanics & Dynamics Simulation (MADSim) Source Code

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Contents

Introduction

Motivation

The industry initiative for creating an open-source repository (Open Source Drilling Community, **OSDC**), for downhole mechanics & dynamics models, is founded on the idea of furthering the industry's knowledge on the topic. In addition, such a repository is an invaluable resource for students and educators who are exploring state-of-the art analysis methods.

Scientific Drilling International (SDI) is an avid promoter of industry collaboration and the education of future generations. As such, SDI is eager to contribute to such an initiative, and aims to support the furthering of the industry as a whole.

> *"If I have seen further it is by standing on the shoulders of Giants"*
> *Isaac Newton, 1675*

Foundational Model

SDI has developed a proprietary BHA/Drillstring model that allows for the calculation of the nonlinear static, linearized dynamic (frequency-domain), and fully non-linear dynamic (time-domain) response of downhole tools. The formulation of this Mechanics & Dynamics Simulation (MADSim) model is based on a three-dimensional nonlinear finite beam element and accounts for a variety of downhole complexities, including:

+ The fully coupled flexibility of the drillstring
+ Geometric nonlinearity (large displacement, small strain)
+ Automatic determination of wellbore contact points
+ Friction acting between the drillstring and the wellbore
+ Three-dimensional wellbore profiles
+ Added fluid mass and damping effects from the hydrodynamic forces generated between the drillstring and surrounding fluid
+ Complex tool geometry (including steerable mud motors, rotary steerable systems, and eccentric stabilizers/components)
+ Shear beam deformations
+ Lateral rotary inertias and gyroscopic effects

The model, whose details can be found in previous research[1], has been validated over the years[2] and has been shown to provide consistent and reliable results.

Simplified Source Code

While SDI cannot provide the source code to the full model that has been developed in-house, there is still a relevant contribution to make. The provided source code is a simplified version of SDI's full mechanics & dynamics model, with the primary motivation of shedding light on the intricacies and complexities of nonlinear finite elements as they relate to drillstring mechanics. In addition, a method for analyzing frictional contact between the drillstring and the wellbore wall, a known difficulty in the industry, is shown in detail.

The simplifications to the source code are listed below:

- Straight wellbores only
- Constant wellbore OD
- No buckling*
- No dynamic calculations
- Graphic user interfaces have been removed
- Advanced plotting features have been removed

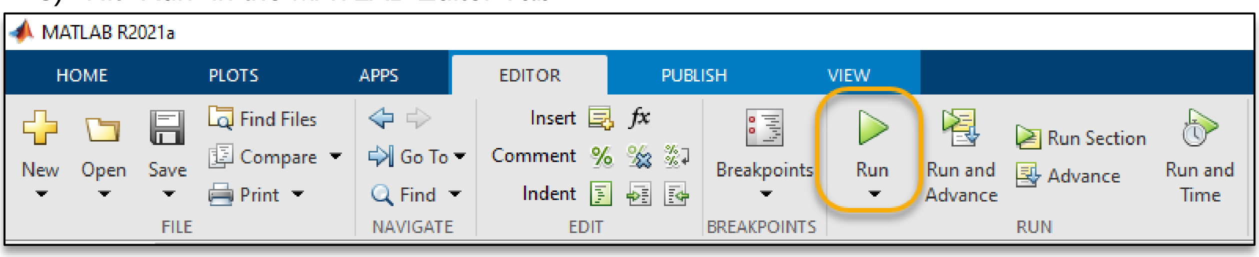
* While buckling algorithms have not been included in the provided source code, the nonlinearity of the model itself will calculate buckling-like deflection. However, buckling/post-buckling deflection must be handled appropriately[3] in order to obtain accurate and realistic results.

Implementation of these features can be seen in the reference literature[1,2]. The open source user is encouraged to pursue adding these when possible, as there are valuable lessons to learn in doing so.

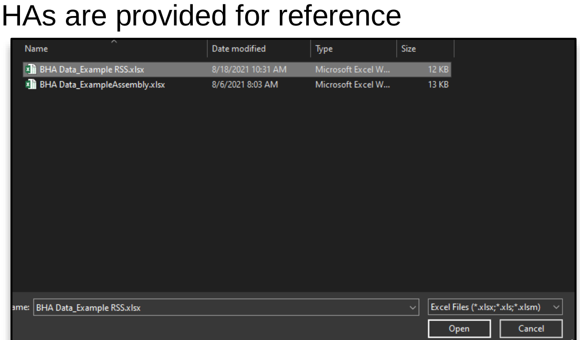
Running the Source Code

Provided as a "quick start" guide to run the source code:

1) Open the file "SDIopenSource_MADSim.m" in MATLAB
   a. File was last updated using MATLAB R2021a. Performance in previous versions of MATLAB cannot be guaranteed.
   b. No additional toolboxes should be required to run, only a single license of MATLAB
2) Adjust necessary "Run Parameters" in the section titled "Data Input and Calculation". Run parameters start on line 77 of the source code.
   a. Model Constraints (Line 87) should not need adjusting for the code as is
3) Hit "Run" in the MATLAB Editor Tab



4) A dialog box will open to select the desired BHA input file. Navigate to the BHA file to be analyzed, and hit "Open". The code should run and generate results.
   a. The appropriate format of BHA files is described later in this document. Two example BHAs are provided for reference



Input Data

Input data to the model comes from two different sources: An excel file containing dimensional information about the BHA, and analysis parameters that are adjusted in the code itself.

Excel BHA File

The BHA dimensions and mechanical properties are imported via an excel file. The data should be organized as described below.

The sheet containing the data must be named "MatLabData"

32	6.75	2.436699	0.25	95	28500000	
33	5.25	2.738613	1.25	95	28500000	
34	5.25	2.738613	1.25	95	28500000	
35	5.25	2.738613	1.25	95	28500000	
36	5.25	2.738613	1.25	95	28500000	
37	6.25	2.738613	0.41665	95	28500000	
38	6.25	2.738613	0.41665	95	28500000	
39	5.25	2.738613	1.25	95	28500000	

MatLabData

Figure 1: Example of Input data from BHA Excel File, Excel sheet naming Convention

Within the "MatLabData" sheet, there should be two main groupings of data: the BHA data, and the stabilizer data. BHA data is contained within columns A though K. Element Data starts on row 2, with the element closest to the bit.

Key information contained within the 1st and 2nd rows of data:

+ Cell C1 = Number of Elements in the model
+ Cell D1 = Number of Stabilizers in the model
+ Cell K2 = Number of Elements below the motor's bend, if modeling a bent mud motor

Dimensional data related to each element is contained within columns A through H:

+ Column A = OD (in)
+ Column B = ID (in)
+ Column C = Length (ft)
+ Column D = Linear Weight (lb/ft)
+ Column E = Young's Modulus (psi)
+ Column F = Poisson's Ratio (no units)
+ Column G = Area moment of Inertia (in^4)
+ Column H = Indicator for which BHA component the element belongs to (1 is the component closest to, or at, the bit)

Columns "I" though "K" are empty, except where mentioned previously

	A	B	C	D	E	F	G	H	I	J	K
1	0	0	105	7	0	0	0	0	0	0	0
2	7.875	1.25	1	100	30000000	0.3	188.667	1	0	0	13
3	6.465	2.25	0.385417	87.64	30000000	0.3	84.4939	2	0	0	0
4	6.465	2.53125	0.148848	87.64	30000000	0.3	83.73679	2	0	0	0
5	6.465	1.5	0.111569	87.64	30000000	0.3	85.50345	2	0	0	0

Figure 2: Example of Input data from BHA Excel File, Columns A through K

Columns Q though W contain stabilizer data. Stabilizers must be located at a node of the assembly:

- Column Q = Node, from the bit, that the stabilizer is located at
- Column R = Empty
- Column S = Empty
- Column T = Empty
- Column U = Stabilizer type indicator
  - 13 = RSS steering pads
  - Other numbers should not be relevant for the source code provided. All other stabilizers/bits will be treated as normal "point contacts"
- Column V = Distance from the Bit
- Column W = Stabilizer blade OD

Q	R	S	T	U	V	W
1	0	0	0	4	0	8.5
45	0	0	0	22	14.75394	6.63
49	0	0	0	22	18.69157	6.63
53	0	0	0	22	22.6292	6.63
57	0	0	0	22	26.56684	6.63
61	0	0	0	22	30.50447	6.63
72	0	0	0	16	36.79584	8.25

Figure 3: Example of Input data from BHA Excel File, Columns Q through W

Code Input Parameters

Analysis parameters and constraints are entered directly into the code. Some operational parameters should be adjusted based on the scenario being analyzed. These parameters include:

- Wellbore inclination (°)
- Weight-on-bit (klbf)
- Torque-on-bit (ft-lbf)
- Mud weight (ppg)
- Wellbore diameter (in)
- Friction coefficient (no units)
- Motor bend angle (°)
- Steer force for a push-the-bit rotary steerable system (lbf)
- Tool-face orientation (°)

Other parameters are considered "model constraints" and should not need to be adjusted too much. These include:

- Convergence criteria
- Wall stiffness
- Number of integration segments for creating elemental vectors and matrices
- Parameters controlling the soft spring stabilization of the model, applied for the first few iterations of the model
- Maximum number of iterations allowed

```
% Run Parameters
inc                 = 90;       % Wellbore Inclination [°]
WOB                 = 35;       % Weight on Bit [klbf]
TOB                 = 5000;     % Torque on Bit [ft-lbf]
MW                  = 10;       % Mud Density [ppg]
DB                  = 8.50;     % Wellbore Diameter [in]
muw                 = 0.0;      % Wellbore Friction Coef. []
BendAngle           = 0;        % Motor Bend Angle [deg]
STEERf              = 4500;     % RSS Steering Force [lbf]
TFO                 = 90;       % Tool Face Orientation [deg]

% Model Constraints
eps                 = 1.0e-6;       % Convergence criteria for static iteration
kw                  = 1.0e8;        % Wall Stiffness - Calibrated from Heisig and Nuebert 2000
z                   = 8;            % Number of Segments for Integration - Simpson's 1/3 Rule. More than 8 not necessary
sd                  = 1000;         % Soft Spring Stabilization - Spring Divisor
ks                  = 6000;         % Initial Spring Stiffness
src                 = 6;            % Spring Implementation Coefficient
                                    %(src = 2 for removal of springs on second iteration)
tc                  = 20;           % Number of iteration to be seen in one iteration window for iteration plots
looplimit           = 300;          % Maximum Number of Static Loops
```

Figure 4: Example of Input data within Source Code, Run Parameters and Model Constraints

Output

The code currently generates calculation results in the form of 3 separate plots: Lateral BHA loading, Lateral BHA deflection, and axial/torsional loading and deflection:

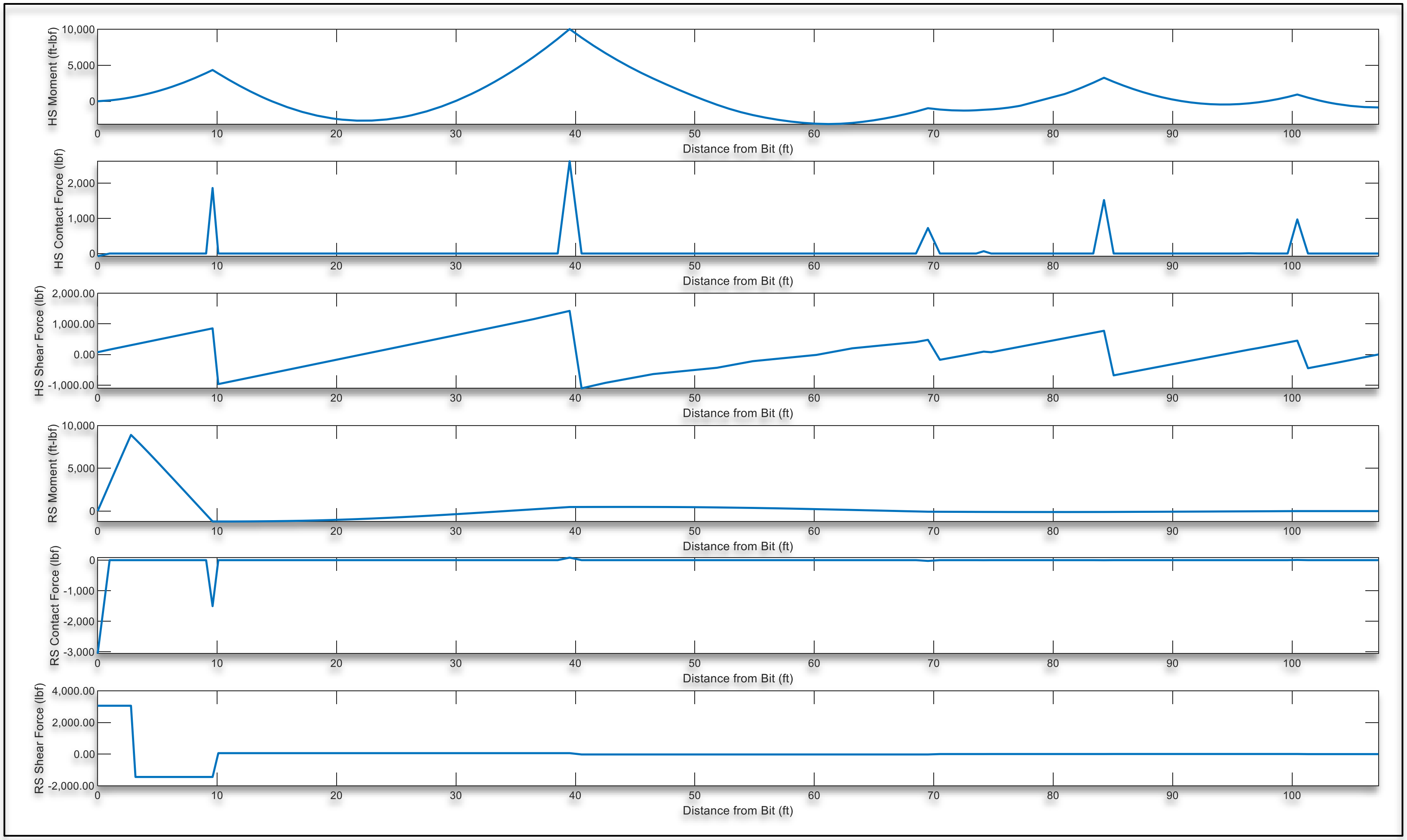


Figure 5: Example of Code Output, Lateral BHA Loading Diagrams

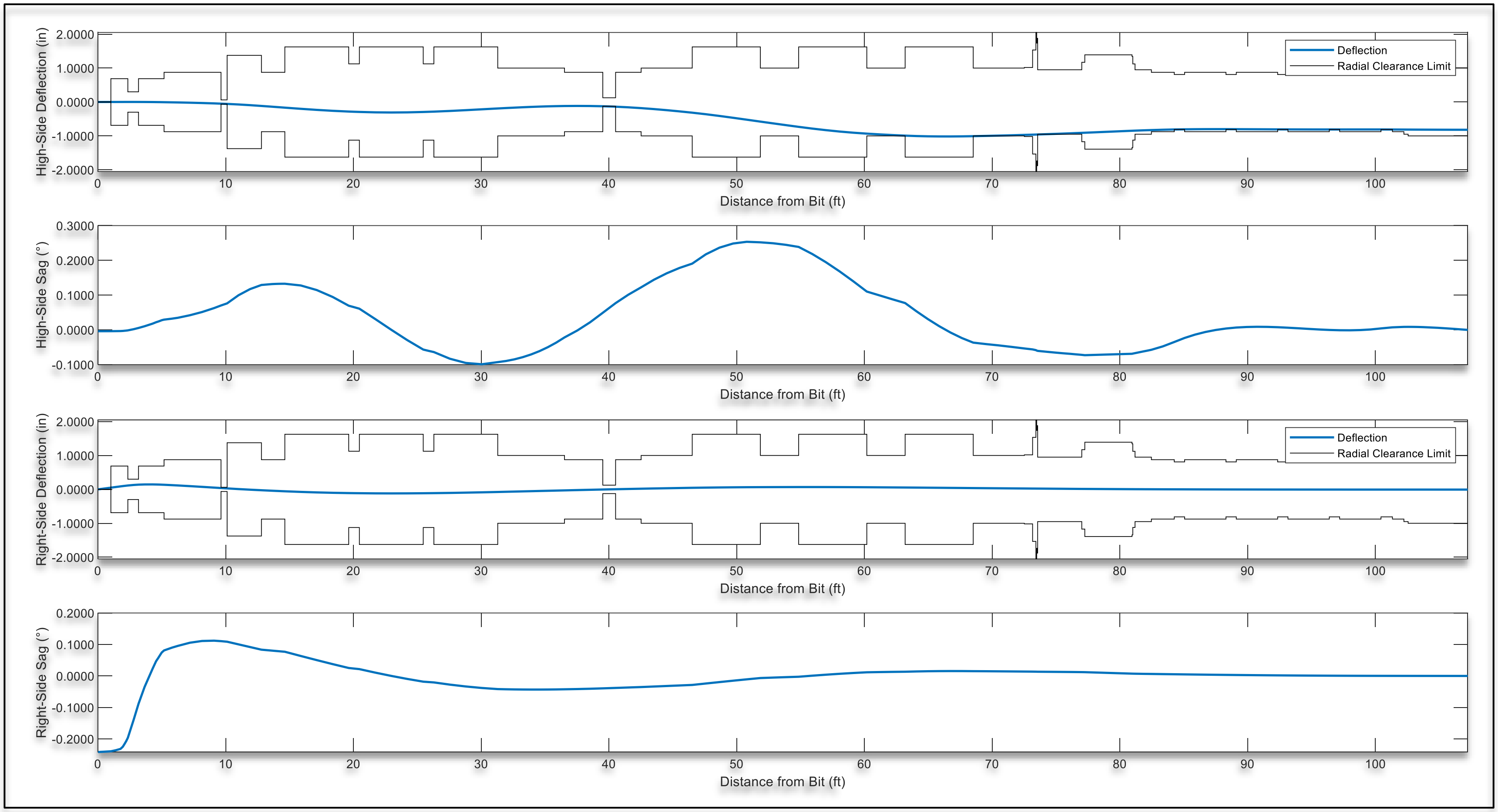


Figure 6: Example of Code Output, Lateral BHA Deflection Diagrams

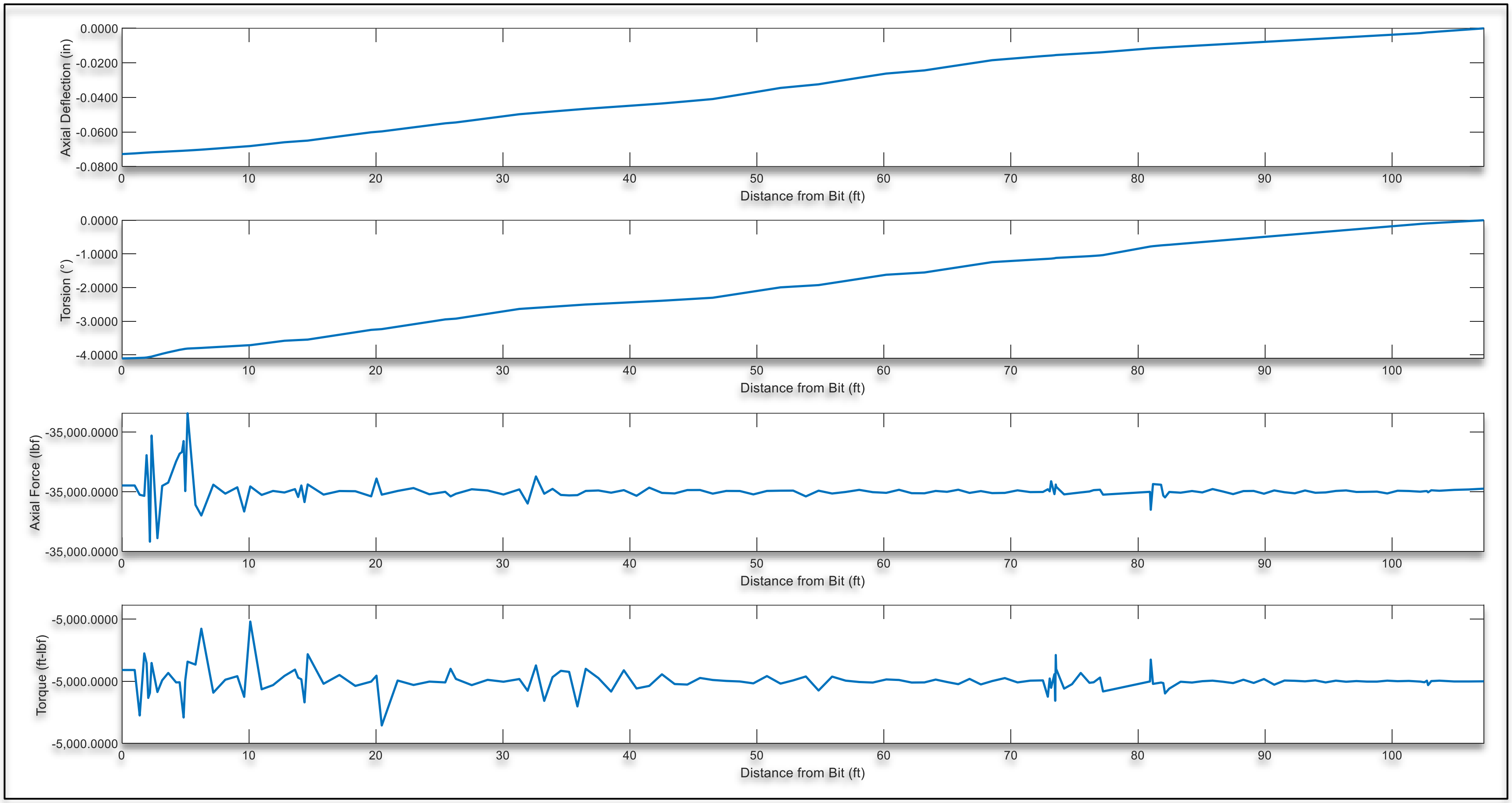


Figure 7: Example of Code Output, Axial/Torsional BHA Loading & Deflection Diagrams

A Challenge to Open Source Users

A tremendous amount of effort has been given to the development of SDI's Mechanics & Dynamics Simulation (MADSim) code. The end result has been a very robust model that provides realistic and meaningful solutions to complicated problems. However, as with anything, there is always room for improvement. The primary limitation of the present model is the calculation time required for more advanced/complex calculations:

- Large assemblies
- Buckling, in some scenarios
- Sensitivity studies
- Time-domain simulation

The largest contributor to this inefficiency is the determination of the location and the magnitude of wellbore contact points, which is generally unknown prior to calculation and is highly dependent on numerous variables (Tubular OD, Wellbore ID, stabilizer clearance, BHA stiffness, fluid effects, trajectory variations, etc.). With this understanding, a challenge is proposed to users of this open-source model:

Can you make a faster model that does not sacrifice accuracy?

In support of answering this question, results for several example calculations are provided. These results have been obtained with SDI's full proprietary model to act as a reference to compare against when developing newer models. The user is referred to the literature for real-word application examples[2,4,5].

Input Data for Comparative Examples

BHA/Drillstring (see "BHA Data_ExampleAssembly.xlsx")

Table 1: Example BHA to be Used for Comparison

Sec No.	Sec Type	Component Description	OD (in)	ID (in)	L (ft)	E (psi)	ν	I (in^4)	ppf (lb_f/ft)	Number of Elements	Length from Bit (ft)
1	Stabilizer - Concent	**Bit Face (Point Contact)**	**8.5**								
2	-	Bit Body, Simplified	7.875	1.25	0.75	30000000	0.3	188.6672	162.9505821	1	0.75
3	-	Simplified Motor, Sec 1 - Bearing Pack	6.5	3	2	30000000	0.3	83.64797	89.62492602	2	2.75
4	Stabilizer - Concent	**, Near-Bit Stabilizer (Point Contact)**	**8.25**								
5	-	, Sec 3 - Bearing Pack	6.5	3	2	30000000	0.3	83.64797	89.62492602	2	4.75
6	Bend	**, Bend**									
7	-	, Sec 4 - Bend Housing	6.5	4	6	30000000	0.3	75.05768	70.75652054	6	10.75
8	Power Section	, Power Section	6.5	5.5	20	30000000	0.3	42.70603	73.99673736	20	30.75
		Power Section Details (7/8-6.4)	**REV/gal**	0.288	**Ecc (in)**	0.256	**$N_{LobesRotor}$**	7	**q_{rot} (lb_f/in)**	2.9	
9	-	, Sec 5 - Top Sub	6.5	3.25	3	30000000	0.3	82.14755	85.41322837	3	33.75
10	-	Non-Mag Stabilizer, Sec 1	6.75	2.875	3	28500000	0.27	98.54886	100.5332229	3	36.75
11	Stabilizer - Concent	**, Stabilizer Blades (Point Contact)**	**8.25**								
12	-	, Sec 2	6.75	2.875	3	28500000	0.27	98.54886	100.5332229	3	39.75
13	-	MWD - Mud Pulse, Non-Mag Collar	6.5	3.25	30	28500000	0.27	82.14755	85.41322837	30	69.75
14	-	MWD - Mud Pulse, Pulser Sub	6.5	3	5.5	28500000	0.27	83.64797	89.62492602	5	75.25
15	-	Non-Mag Drill Collar	6.5	3.25	30	28500000	0.27	82.14755	85.41322837	30	105.25

Table 2: Analysis Parameters used for Comparative Analysis

PARAMETER	VALUE	UNITS
WEIGHT-ON-BIT	30	klbf
TORQUE-ON-BIT	3500	ft-lbf
MUD WEIGHT	10	lbm/gal
MOTOR BEND ANGLE	1.75	°
WELLBORE DIAMETER	8.5	in
FRICTION COEFFICIENT	0	-
STARTING INCLINATION (FOR BUILD RATES)	60	°

Table 3: Dummy Survey for Horizontal Turn, used for Comparative Analysis

MD (FT)	INCL (°)	AZIM (°)
0	90	180
55	90	185.5
110	90	191

Results of Comparative Data Set

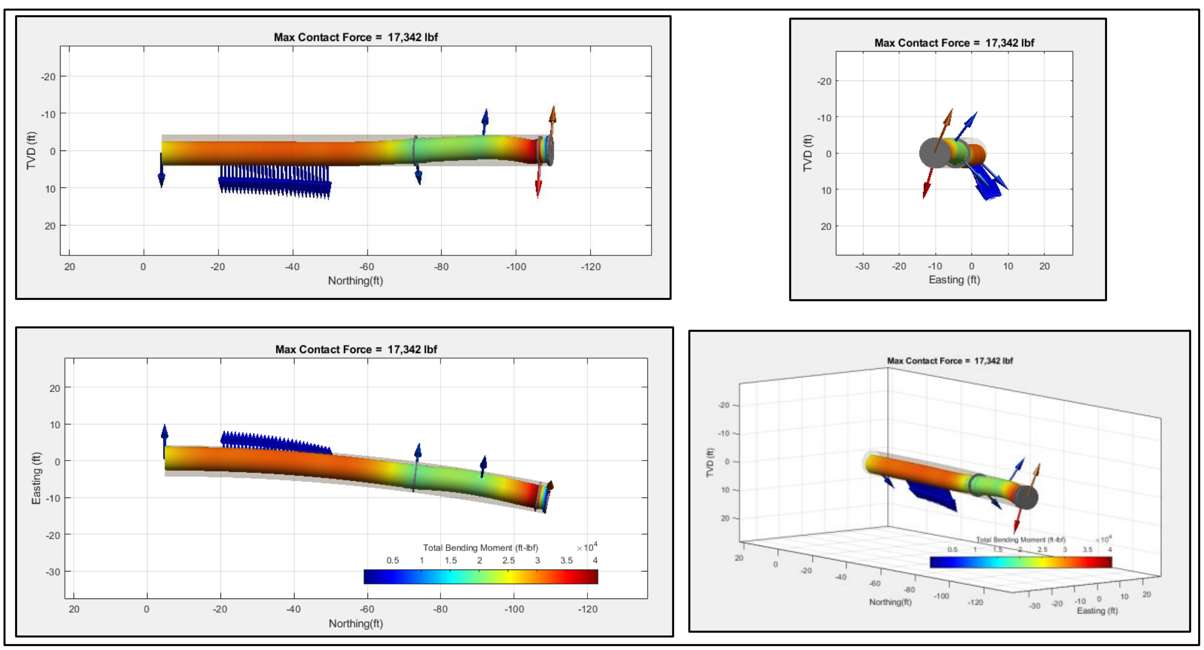


Figure 8: Deflection of Example BHA in a 10°/100ft turn.(See Tables 2 and 3 & "Results_Loading_ExampleAssemblyTurn.xlsx")

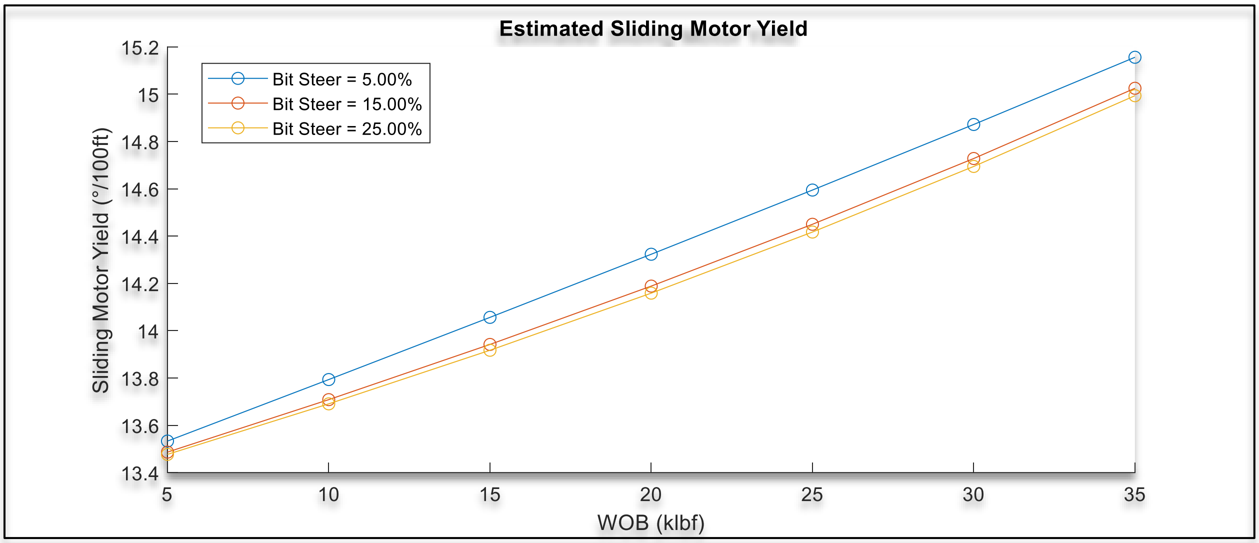


Figure 9: Motor Yield Estimation (See Table 2 & "Results_MotorYield (Sliding)_Example Assembly.xlsx")

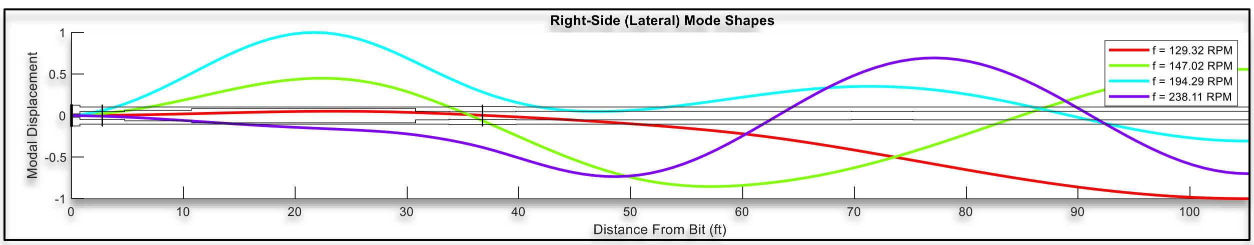


Figure 10: Linearized Natural Frequencies, expressed as Critical RPMs, and Mode Shapes. Straight, Horizontal Wellbore (See Table 2)

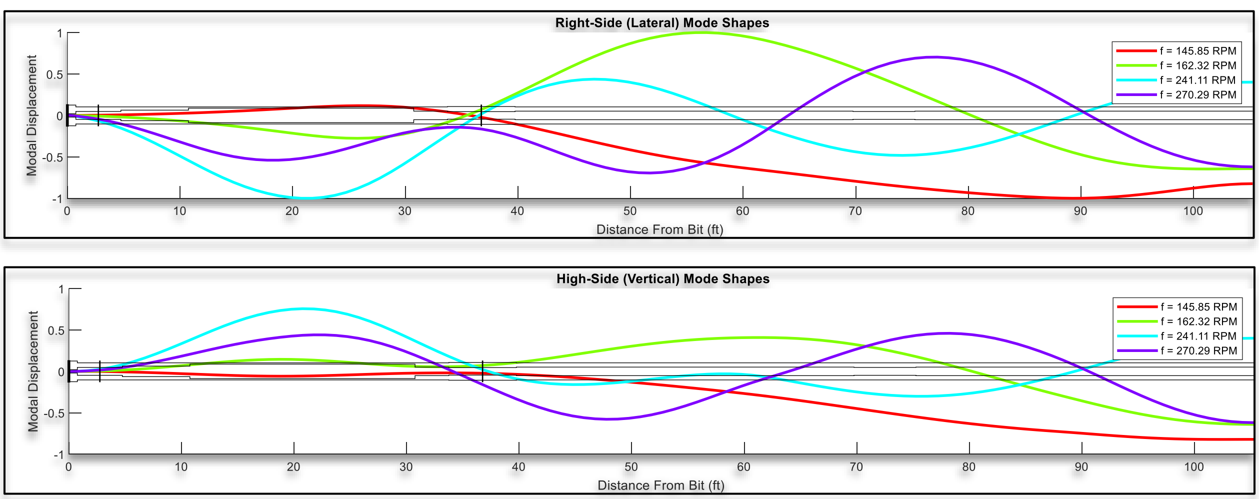


Figure 11: Linearized Natural Frequencies, expressed as Critical RPMs, and Mode Shapes. Curved Wellbore, 10°/100ft turn (See Dummy Survey in Table 3)

References

1) Wilson, J.K. 2017. “Nonlinear Drillstring Modeling with Application to Induced Vibrations in Unconventional Horizontal Wells”. Ph.D. Dissertation. Texas A&M University.

2) Wilson, J.K. 2019. “Field Validation of a New Bottomhole-Assembly Model for Unconventional Shale Plays”. SPE-191780-PA. SPE Drilling & Completion.

3) Heisig, G. 1995. “Postbuckling Analysis of Drillstrings Using the Finite-Element Method”. ASME Drilling Technology, Vol.65.

4) Wilson, J.K. 2018. “Field Validation of New BHA Model and Practical Case Studies in Unconventional Shale Plays, with a Framework for Automated Analysis for Operations Support”. SPE-191780-18ERM-MS. SPE Eastern Regional Meeting. Pittsburg, PA.

5) Wilson, J.K., Heisig, G., Freyer, C. 2022. “HFTO Solved: Proven Mitigation of High Frequency Torsional Oscillations in Motor-Assisted Rotary Steerable Applications”. SPE-208739-MS. To be presented at the IADC/SPE Drilling Conference and Exhibition. Galveston, TX.