NOVEL, FULL 3D MECHANICAL MODEL IMPROVES DESIGN AND ANALYSIS OF SUCKER ROD PUMPING SYSTEMS IN DEVIATED WELLS

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ABSTRACT

Design and analysis of sucker rod systems in deviated wells has challenged industry practitioners. Historical adaptations of the wave equation solution struggle with 3-dimensional wellbore trajectories and other system complexities. A unique finite element model calculates rod-dynamics in 3 dimensions. The model can predict or analyze motion of the rod string at any location in the well. Frictional forces and buckling tendencies are also simulated. The model is embodied in advanced computer software which also provides a sophisticated, interactive visualization of simulation results. Through superior modeling, sucker rod system design and operating parameters can be optimized to reduce mechanical wear and component failures.

INTRODUCTION

Modern rod pump system designers employ modeling software to predict system performance. Operations personnel analyze installed systems with diagnostic models which transform surface load and position information into estimated pump dynamometer cards. When these diagnostic models produce accurate results, autonomous on-site controllers can diagnose each downhole pump stroke and make control decisions about pumping speed and/or fault conditions. For more than 50 years, the industry has relied on proven models to design, analyze, and automate reciprocating rod pumping systems in vertical wells.

Over recent decades, oil producers have increasingly employed directional drilling practices to exploit unconventional reserves. These deviated wells present many challenges for artificial lift equipment. Reciprocating sucker rods experience mechanical friction, and other complex forces when employed in non-vertical orientations. If operators are to properly design, analyze, and optimize these systems, advanced modeling software must account for all static and dynamic effects experienced in deviated wells.

BACKGROUND

In the 1960’s, Gibbs [1] developed techniques for applying the One-Dimensional Damped Wave Equation (1DDWE) to reciprocating sucker rod pumping applications. His original equation was given as:

$$\frac{\delta^2 u(x,t)}{\delta t^2} = a^2 \frac{\delta^2 u(x,t)}{\delta x^2} - \frac{\pi a v}{2L}\frac{\delta u(x,t)}{\delta t}$$

In this equation,

u is displacement along the x direction (axial to rods)
t is time
a is speed of sound in the sucker rod material
v is the viscous damping factor
L is the length of the rod string

For decades, the oil industry has used this 1DDWE model to both predict performance of rod pumping systems and to diagnose operation of these systems. This model has proved to be effective in most applications. The models incorporating various solutions to the 1DDWE were eventually validated using a set of data collected by Sandia Labs, which employed downhole dynamometer instruments designed by Albert [2,3].

The exceptional cases - where the 1DDWE models have failed to produce acceptable results - often correlate to known wellbore tortuosity. Investigators speculated that these installations were probably being influenced by mechanical friction between rods and tubing.

Although the 1DDWE is capable of modeling speed-dependent friction, it contains no provision for the type of (Coulomb) friction which exists when rods are forced to slide against the tubing.

In an effort to address this mechanical friction, industry practitioners sometimes attempted to divide the rod string into multiple taper sections – assigning different upstroke and downstroke damping factors to each taper. Using iterative applications of this technique, beam pumping experts could empirically tune 1DDWE models to derive believable results – for a given well, rod string, pump, and pumping unit configuration.

1DDWE AND DEVIATED WELLS

As directional drilling permeated the onshore oil business in the U.S., it became clear that the 1DDWE could not accurately model sucker rod pumping systems in highly deviated wells.

Investigators quickly concluded that Coulomb friction must be incorporated into deviated well models. Various practitioners derived methods to superimpose mechanical (Coulomb) friction upon the wave equation solution. Different formulations were proposed to model the bending of the rod string and the resulting rod-tubing normal forces. A friction factor could then be applied to estimate the mechanical force opposing the motion of the rods. These Coulomb friction forces were then superimposed on the wave equation solution at various discrete locations in the rod string.

In developing these models, researchers decomposed the static and dynamic portions of the system. Gravitational and buoyant forces were combined with bending moments required to contort the rod string into the specified wellbore geometry. The resulting frictional forces were added to a dynamic 1DDWE model.

Such models are widely used today, often producing believable results in predictive mode. For this discussion, models which add Coulomb friction to a conventional 1DDWE solution will be addressed as WE+CF models.

Even with significant investment, the WE+CF class of models have not been entirely successful – especially in diagnostic mode. These models frequently produce anomalies at the reversal points in the downhole card – as depicted in Figure 1. It has been speculated that these anomalies are related to one or more of the following phenomena:

- Static – vs dynamic - friction factors might need to be applied when rod string stops moving at a contact point and then resumes motion
- Inability of the models to precisely predict direction of motion – and thereby properly apply the direction of the frictional force – when rod speeds are near zero.

The intense industry effort to accurately model reciprocating rod pump systems in deviated wells has been overshadowed by the absence of data with which to validate available models. The authors know of no publicly-available downhole dynamometer data from deviated wells.

FINITE ELEMENT MODELING

In efforts to address the aforementioned challenges, researchers have returned to first principals approaches to develop new models. Eisner et al [4] provide a thorough review of these efforts. Almost universally, these researchers have turned to Finite Element Modeling (FEM) analysis – which is made practical by dramatic advances in computer technology.

With FEM, the sucker rod string can be represented as spatial beam elements having 6 degrees of freedom at each end:

- Displacement in the X-direction
- Displacement in the Y-direction
- Displacement in the Z-direction
- Rotation around the X-axis
- Rotation around the Y-axis
- Rotation around the Z-axis

This analysis permits much more sophisticated modeling of the sucker rod string – including

- Axial distortions and vibrations (X displacement)
- Lateral distortion and vibrations (Y and Z displacement)
- Bending forces and vibrations (Y, Z rotation)
- Torsional forces and vibrations (X rotation)

Eisner et al formulated an approach to predictive modeling of sucker rod systems by configuring a commercial FEM software product (Abaqus 2020) to solve a model which they designed. This software implementation could apparently only be used in predictive mode. In their words…

"The nature of the FEM does not allow the direct evaluation of the plunger load, based on polished rod load and position."[4]

They demonstrated an algorithm for using this predictive model in an iterative fashion to predict a surface card which matched an observed pump card. Their algorithm involved multiple executions of the model for each time step of the pumping unit stroke.

CUSTOM-DESIGNED ALOGORITHM

Although researchers have used Finite Element techniques to model reciprocating rod pumping systems, FEM of sucker rod systems has not been available to mainstream practitioners. The authors have developed the ROD3D model which is an application-specific Finite Element formulation requiring minimal configuration. In fact, this new model utilizes the same input parameters required by commercial WE+CF software. This model has been embedded into practical, intuitive software which is as simple to use as traditional rod pump design and diagnostic software.

ROD3D - FULLY 3-D MODEL

The model developed here considers the rod string as a fully three-dimensional circular cross-section beam – see Figure 2. This permits the model to account for the complex effects of the fully three-dimensional static and dynamic forces acting on the rod string, which are:

1. Axial forces.
2. Bending in the YZ plane.

3. Torsion around the axial direction (X).
4. Mass damping.
5. Coulomb Friction.

This results in an element with 6 degrees of freedom at either end.

This allows modeling of real rod string trajectories in 3D, not just in plane (2D) deviations.

Trajectories are entered as a series of points in 3D space. The rod string is then fitted to this trajectory as though lowered into place. The initial loads due to bending and static loading (under gravity) are estimated. The surface pump motion is then applied to the top of the rod string and the ensuing displacements are calculated at the end points (nodes) of the beam elements as the solution marches through time.

Note that the trajectory can be considered as a series of straight-line vectors, but this would result in very high bending stresses at the changes in direction just for the placement. However, an alternative is to create a spline through the trajectory points and have the rod string conform to that form. Whichever method is chosen, it is possible to recreate the real trajectory closely and determine the related initial stresses.

Figures 3 shows an example wellbore profile in North-South (Left), East-West (Center), and Isometric (Right) projections. Above the kickoff point, most of the deviation in this trajectory is in the East-West orientation.

If a 2-dimensional model were applied to this wellbore trajectory one could use projections in either:

- The plane containing the vertical axis and the North-South axis (Figure 3, Left)
- The plane containing the vertical axis and the East-West axis (as in Figure 3, Center)

Alternatively, an artificial triangulated pseudo-trajectory could be derived using the deviation from vertical. Such a pseudo-trajectory is illustrated in Figure 4.

Using the example pumping system parameters presented in Table 1, the 3-D Finite Element predictive model was run at 6 strokes per minute. Four runs were performed using the different well trajectories:

- North-South Projection
- East-West Projection
- Triangulated Pseudo-Trajectory
- Full 3-Dimensional Trajectory

The pump in these cases is situated above the kickoff point. Splines were used to connect the survey points.

As can be seen in Figure 5, the 2-D trajectories produce surface cards with varying degrees of deviation from the surface card produced using the full 3-D model.

Figure 6 shows the Coulomb friction force vs surface stroke position for the model cases. Note that the triangulated pseudo-trajectory case resulted in higher Coulomb friction than the 3-D case.

These results demonstrate the benefit of the full 3-D model over 2-D formulations.

<u>BOUNDARY CONDITIONS – PREDICTIVE CASE</u>

In Predictive mode, the standard boundary conditions (BCs) detailed in Gibb's [1] are applied, which are (in simple terms):

1. The displacement applied at the polished rod due to the surface pumping unit kinematics.
2. An idealized version of the downhole pump behavior – i.e., no DH pump movement until a force equal to the weight of the fluid column is reached, no increase in load at the DH pump during the upstroke, no displacement as the fluid column load is shed and freefall on the downstroke once all the fluid load is shed.

Other downhole BCs such as the fluid pound phenomenon which can occur when the traveling valve reaches the fluid surface in a partially-filled pump barrel or the gradual load transfer that can occur due to gas interference can also be applied.

HETEROGENEOUS ROD STRING MODELING

For non-continuous rod installations, the rod string has couplings joining each section. These couplings increase the mass of the system while also impacting the stiffness and damping of the system. Whereas traditional wave equation solutions treat the rod string as a continuous rod, full derivations to formulate the effect of the added mass on both stiffness and damping have been incorporated this into the model. There are two associated parameters:

1. The added mass percentage.
2. The percentage of the rod string over which this added mass is distributed.

In this manner, depending on the real geometry of the joints, the mass increase and length of the coupling can be set to accurately reflect the effect it will have on the system. Figure 7 shows the simplified geometry used to model couplings.

As with traditional modeling software, the ROD3D model also accommodates tapered strings and strings comprised of different materials.

BUOYANCY MODELING

The historical industry discussion about True Loads vs Effective Loads [5] addressed the impact of buoyant forces on rod buckling in vertical wells. Although the observations of the Effective Load advocates seem to have credence – as they pertain to rod buckling tendency – care must be exercised in modeling the impact of the hydrostatic fluid forces surrounding the rods

The standard approach to modelling buoyancy is to ensure that the results are plotted showing a zero force at the down hole valve during the downstroke (effective loads). To achieve this, while also making sure that the PR force is a true reflection of the buoyancy, the simplest approach is to use an effective rod string density – that is, to reduce the rod density by an amount equivalent to the fluid density for the purposes of calculating the static load.

This approach is acceptable in vertical wells because the models assume all forces to be in the vertical direction and all components in the wellbore are also oriented vertically and are radially symmetrical around the vertical axis.

The true effect of buoyancy becomes even more complex when modelling a deviated well because the buoyancy effect is not felt uniformly along the rod string. Buoyancy is the result of the hydrostatic fluid pressure acting normal to all submerged surfaces. It must be explicitly incorporated as such a surface force – accounting for local fluid pressure and local orientation of the submerged rods. This is further complicated by the presence of the couplings, which also contribute to an axially oriented buoyancy force. The true equations for these buoyancy forces have been derived and incorporated in the ROD3D model - using the simplified coupling geometry show in Figure 7.

EVALUATING ROD STRESSES AND STRESS RANGES

Without reliable design and diagnostic tools, many operators have adopted the “long and slow” strategy for their deviated rod pumping installations. That is, they employ long-stroke pumping units and run these units at relatively low stroke rates. This approach reduces rod string dynamics and should result in surface dynamometer cards which more closely resemble their downhole counterparts. Using these techniques, pumping units can be controlled from surface card setpoints (or their force- translated counterpart pump cards), and anomalies in diagnostic downhole cards are minimized. However, the “long and slow” strategy limits the dynamic range of the sucker rod pumping system – sometimes excluding rod pumping for consideration when high fluid volumes need to be lifted.

As pumping unit speeds are increased, rod velocities and reversal accelerations are amplified. Without reliable models, practitioners cannot discern how far they can push their systems to gain dynamic pumping range while still maintaining tolerable rod stress ranges. Of particular concern is the possibility of subjecting lower sections of the rod string to compression and/ or the phenomenon commonly termed buckling tendency.

The ROD3D model computes rod stresses (tension and compression) for the entire rod string at every time step within the stroke.

Using these stresses, sections which experience excessive stress range or compression can be addressed through either a change to surface stroke motion profile or by employing downhole components which effectively increase rod stiffness (guides, sinker bars). Subsequent model runs can be used to predict the performance of different remediation approaches. Since the model runtimes are negligible, these types of analyses are practical.

ROD GUIDES

Rod guides are used to reduce friction wear and to reduce the tendency of the rod string to buckle. This works because they reduce the effective length of any section, thereby increasing the load required to cause buckling (as per Euler Buckling) by a squared factor – e.g., reduce the effective length by a half increase the buckling load by a factor of 4. In the ROD3D model, the “tendency” to buckle is calculated, by simply comparing the compressive load in any section to the Euler Buckling load for that section – based on an assumed effective length. This simple calculation facilitates a sensitivity analysis on a given rod string configuration to predict how rod guide spacing would reduce the risk of buckling.

The ROD3D model assumes that the couplings allow rotation, meaning that (for Euler Buckling calculations) either end of the strut in question is pinned. This assumption is also applied to rod guides. Of course, this assumption means that the estimate of tendency to buckle is conservative (that is, the effective length used will lead to a lower critical load, and therefore a higher tendency to buckle).

Figure 8 shows a rod string with a significant deviation. The image is capturing the tendency to buckle on the downstroke, assuming that the couplings are acting like rod guides. As this example illustrates, the compressive force in the section shown in red is exceeding the critical Euler load.

Figure 9 illustrates the impact of reducing the spacing between rod guides to 6m. The risk of buckling has been eliminated.

Note that the buckling tendency graphed in Figures 8 & 9 are calculated based on the simplified buoyancy (reduced density) - which is inaccurate, but removes the portion of the compression in the lower section due to the significant hydrostatic pressure at the DH pump. So, the compressive forces are due solely to the dynamic forces resulting from the PR motion.

However, the true compressive forces in the rod string are show in Figures 10 & 11 (using the more rigorous buoyancy model developed herein). Estimating the influence of the true compressive forces on the buckling tendency of the rod string are beyond the scope of this paper.

DIAGNOSTIC MODE

The ROD3D model also includes a diagnostic formulation for computing downhole pump cards from observed surface dynamometer data. The formulation developed is novel and unique and calculates the force and displacement at all points in the rod string from using a PR card as input. As with the predictive model, diagnostic runtimes are a matter of seconds.

In the absence of real data, the diagnostic model will be demonstrated by using synthetic data – that is, the PR card from a predictive model will be used as input for the diagnostic model. The logic here is that, if it is accepted that the predictive model is correct, then, if the diagnostic model can calculate the down hole conditions (as per the predictive model) from the predictive PR card, it is validated.

The left-hand pane in Figure 12 shows the results of a predictive model simulation. The rod string comprises 200 1-inch bars. The well trajectory is fully 3 dimensional. In predictive mode, it is run using the C-912-D-365-168 pumping unit in Table 1 at 6 SPM. The right-hand pane shows the output of the diagnostic model using the PR card from the predictive model. Figure 13 shows these two results superposed. It is a close match, with a slight instability (muted versions of the anomalies depicted in Figure 1) at the pump reversal points.

Investigation of the nature of the instability that occurs in the diagnostic solution revealed that it could be circumvented by application of a case-by-case correction. However, this is only a temporary solution and further work is needed to fully automate this correction process. Figure 14 shows the resulting diagnostic down hole card once the correction is applied.

The significance of the ability of the model to cater for fully 3D trajectories is illustrated in Figures 15, 16, and 17. In this case the earlier model is used, as per Table 1, with the real 3D trajectory as per Figure 3 - Right. In addition, the predictive model includes the added complexity of pump off at 75% fillage. Figure 15 shows the inaccuracy of using the East-West 2D trajectory of Figure 3 (b) to try and calculate the DH card in diagnostic mode. Similarly, Figure 16 shows the inaccuracy of the pseudo 3D trajectory of Figure 4. However, when the correct, fully 3D trajectory is used, Figure 17 clearly shows a close match.

CONCLUSIONS

Although software products based on the One-Dimensional Damped Wave Equation have successfully modeled rod string dynamics in vertical wells for decades, Finite Element Modeling can more precisely compute the influences of friction, buoyancy, and rod guides in wells with 3-dimensional trajectories. In recent years, researchers have turned to Finite Element Modeling to investigate sucker rod dynamics in deviated wells. Usually, significant expertise has been required to configure, prepare data for, and visualize the output of FEM tools employed for rod pumping applications. Therefore, FEM modeling has not been available to industry practitioners for day-to-day design and diagnostic tasks.

ROD3D is a novel, tailored Finite Element model developed specifically to solve the dynamic rod string problem. It incorporates the fully 3D geometry of a deviated well and accounts for the complex Coulomb friction forces that ensue. It is embodied in software that can be simply configured – using the information typically provided to sucker rod design and analysis software. The simulation cases run nearly instantaneously – allowing industry personnel to rapidly investigate multiple scenarios for a single well. Application-specific user interface components expose the model results in an intuitive fashion.

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TABLES

Table 1 - Pumping System Parameters Used in Example Calculations

Parameter	Value	Units of Measure
Pumping Unit	C-912-D-365-168	API
API Dimensions:		
A	210	inch
C	120	Inch
I	120	Inch
P	148.5	Inch
H	262	Inch
G	111	Inch
K	192.9	Inch
R	47	Inch
Downhole Pump Diameter	1.5	inch
Fluid Density	1000	Kg/m^3
Top Rod Taper:		
Material	Steel	
Diameter	1	Inch
Weight with Couplings	32.9	Kg/rod
2nd Rod Taper:		
Material	Steel	
Diameter	0.75	Inch
Weight with Couplings	18.1	Kg/rod

FIGURES

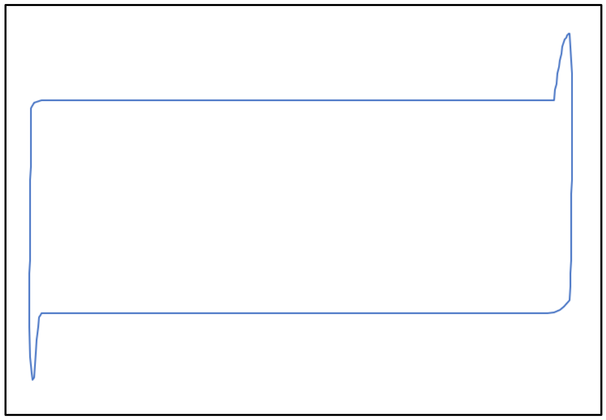

Figure 1 - Characteristic Downhole (Diagnostic) Dynagraph from WE+CF model in deviated well

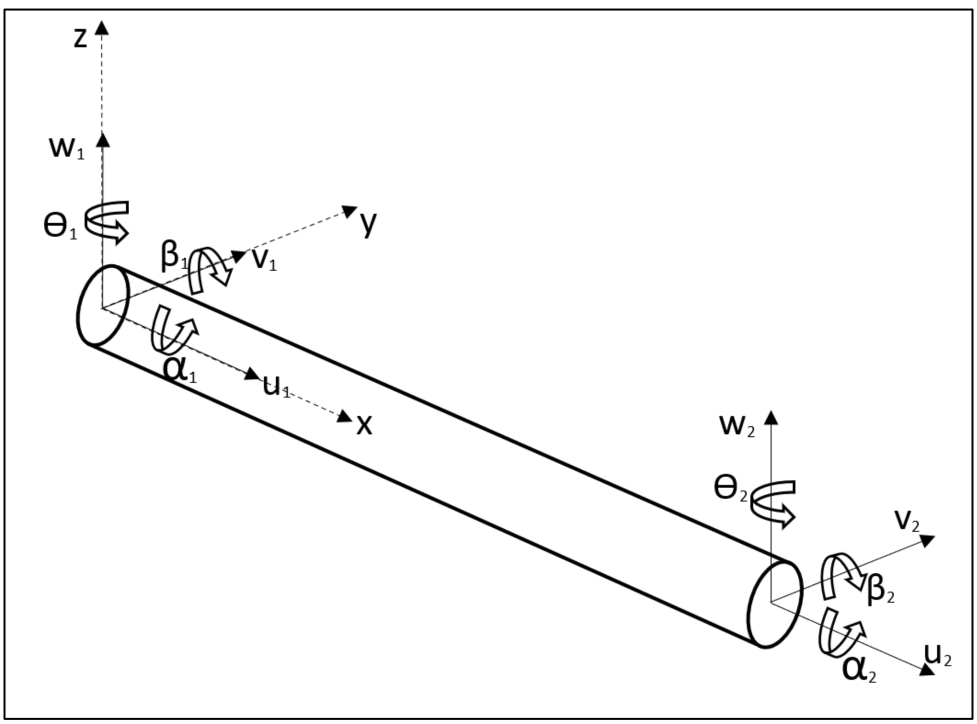

Figure 2 - The rod string is modelled as a set of 3D beam elements with 12 degrees of freedom.

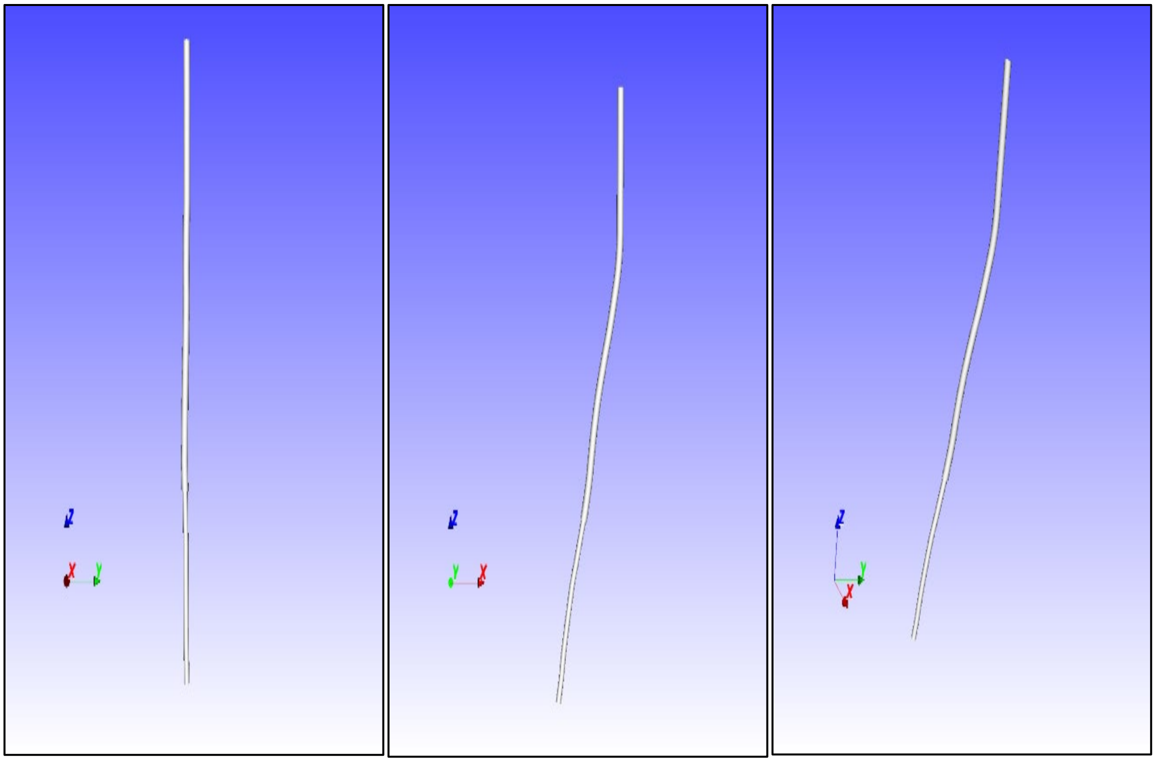

Figure 3 - Example well trajectory in North-South (Left), East-West (Center) and Isometric (Right) Projections

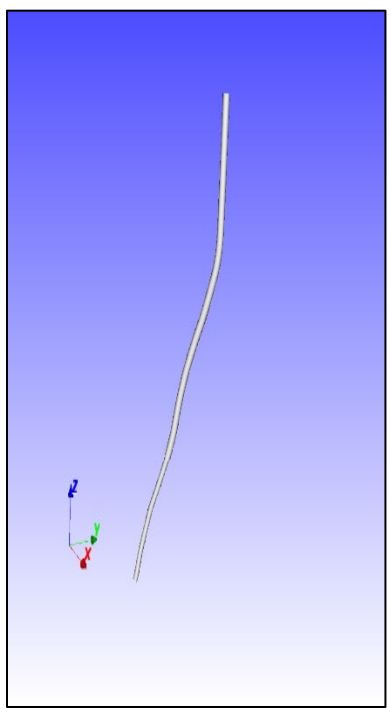

Figure 4- A 2-D Pseudo-trajectory Derived from 3-D Directional Survey

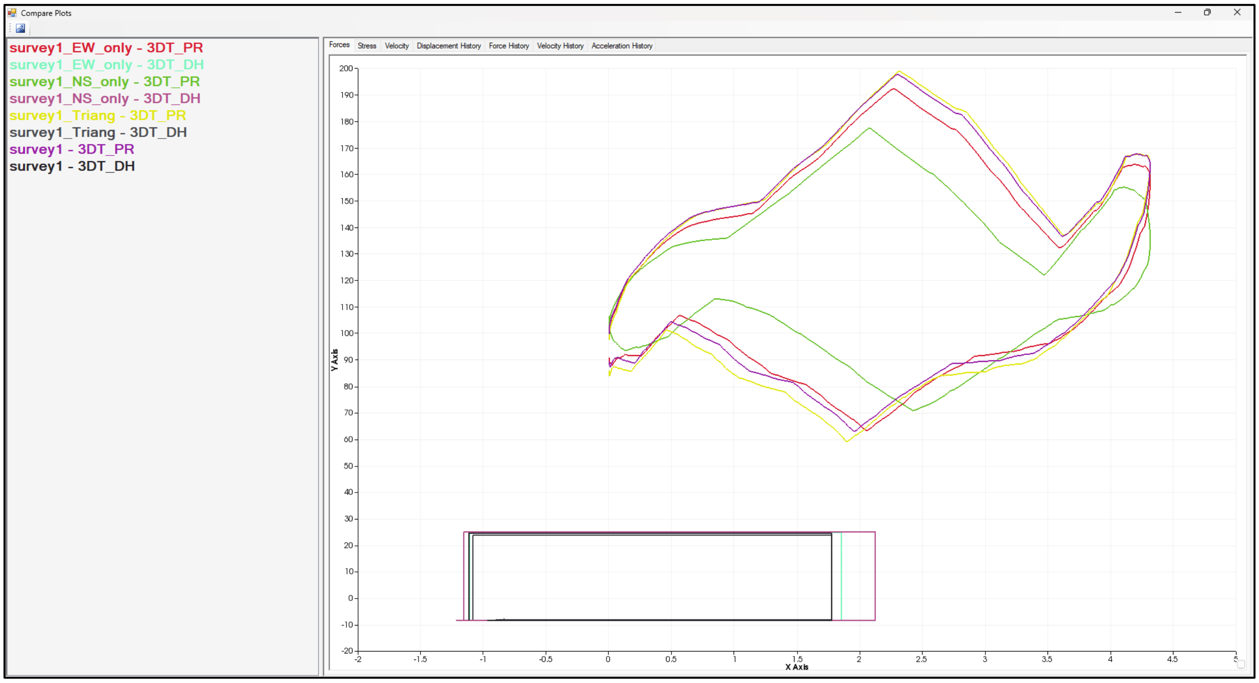

Figure 5 - Model Results for Different 2-D approximations vs Full 3-D

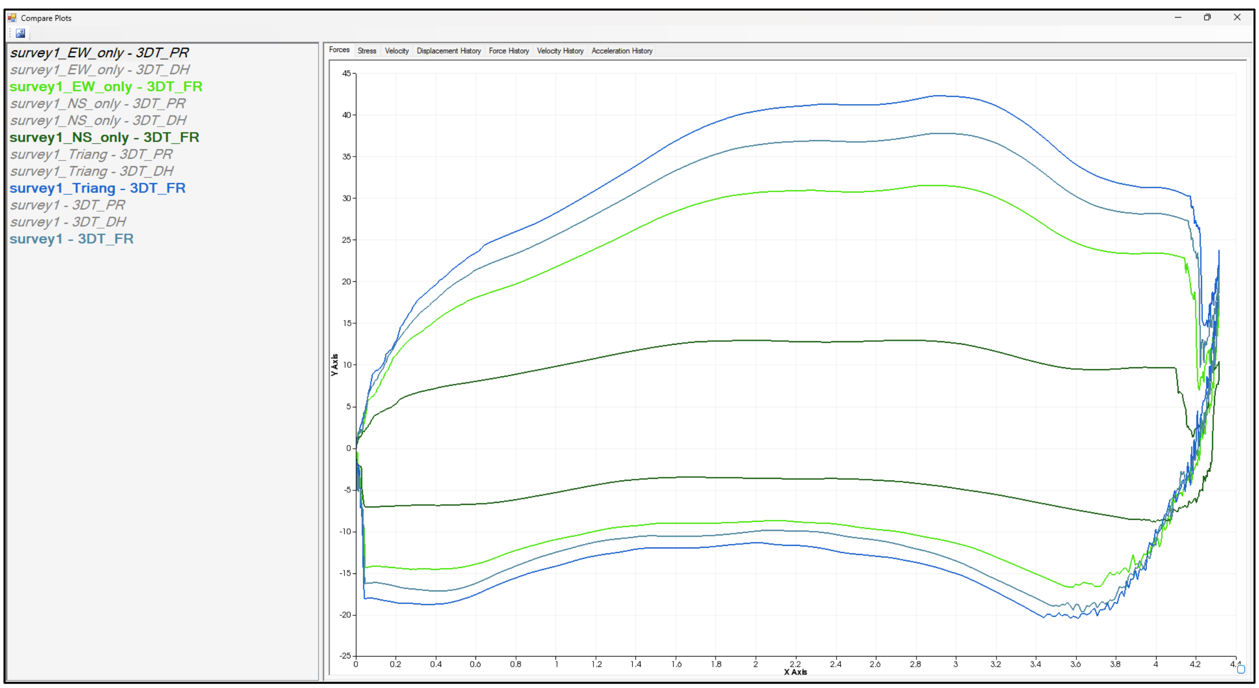

Figure 6 - Model Coulomb Friction vs Surface Position for Different 2-D approximations vs Full 3-D

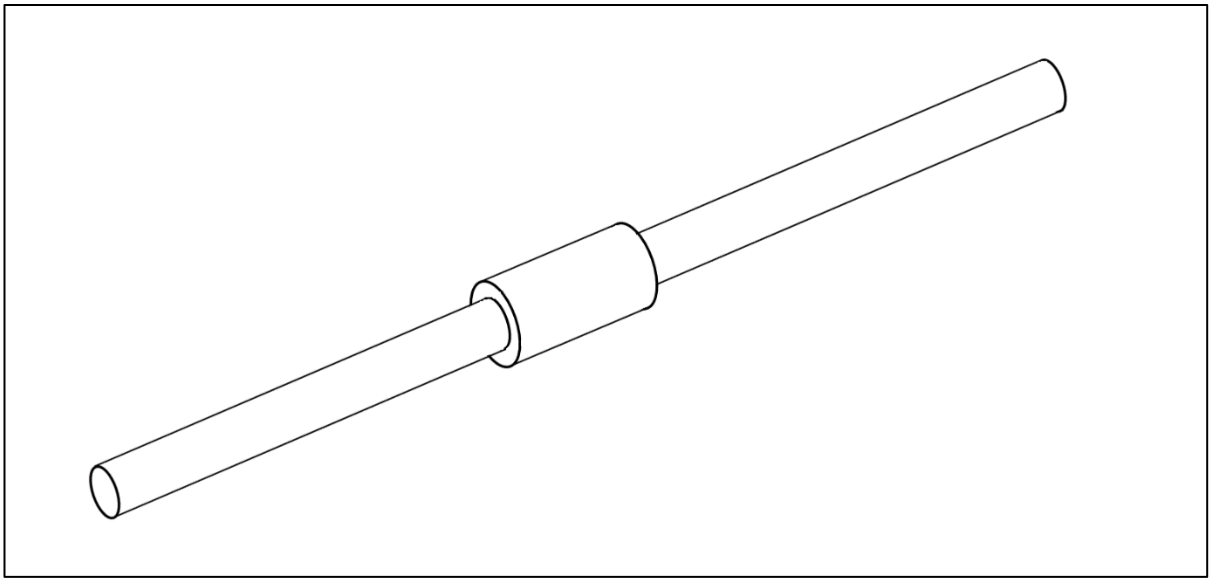

Figure 7 - The couplings are modelled as thicker sections of rod string.

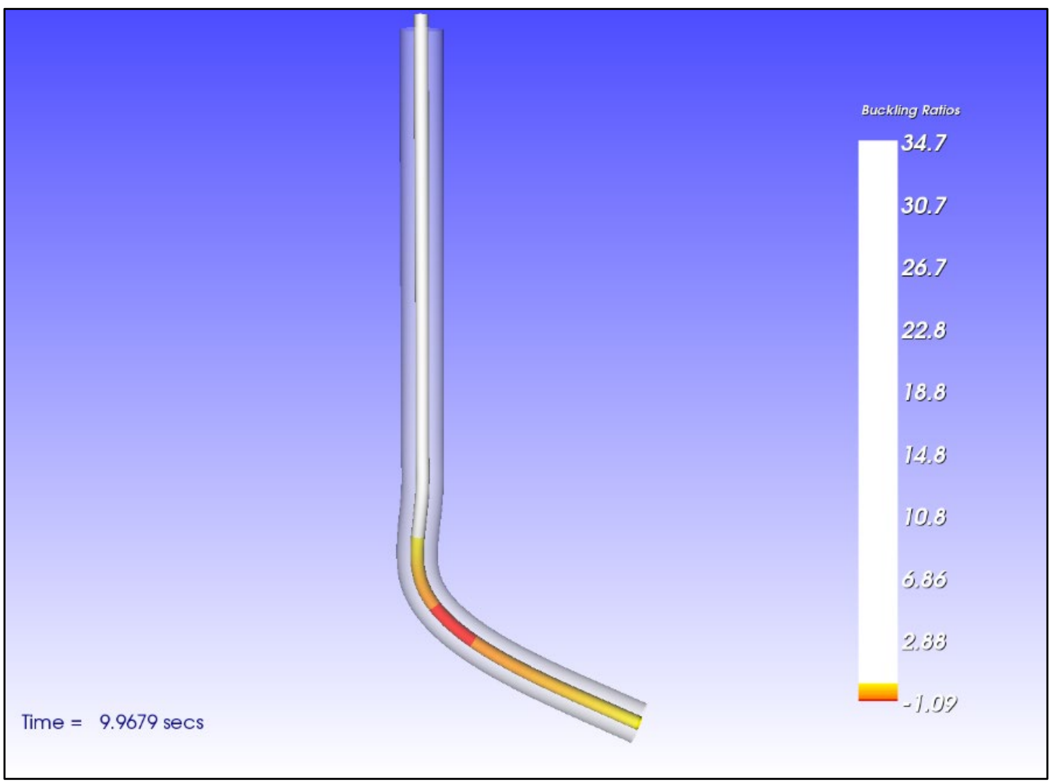

Figure 8 - Almost 10 secs into a 15 sec pump cycle, a section of the rod string is at risk of buckling.

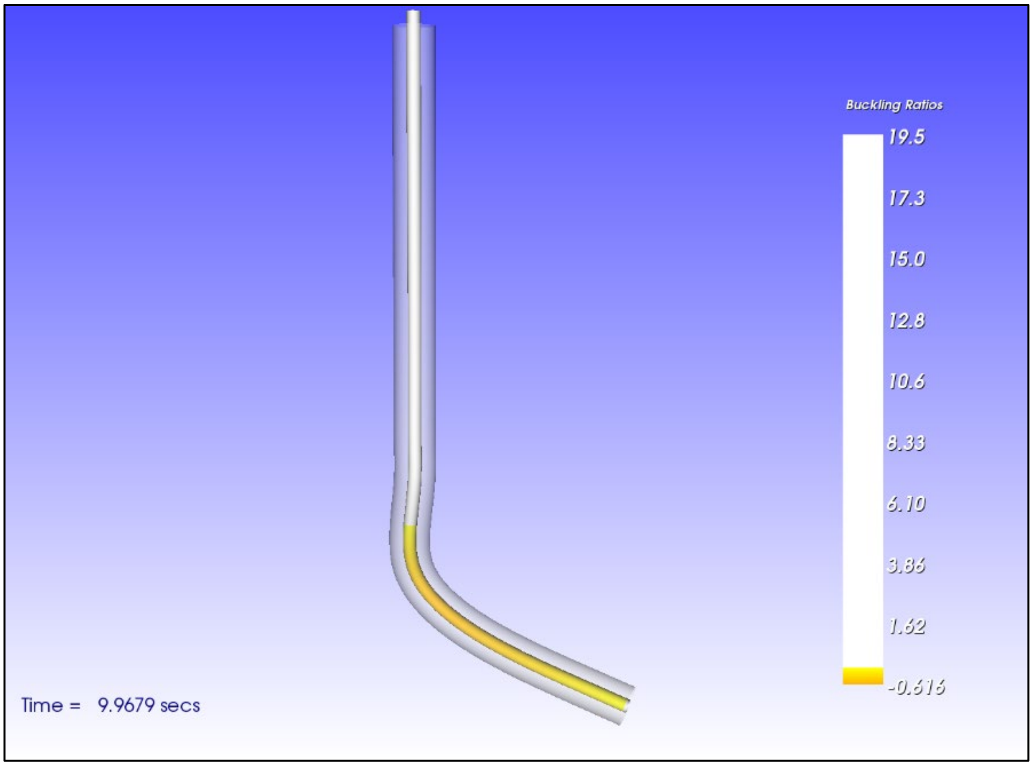

Figure 9 - By reducing the rod guide spacing to 6m (from 8m), the risk of buckling is eliminated.

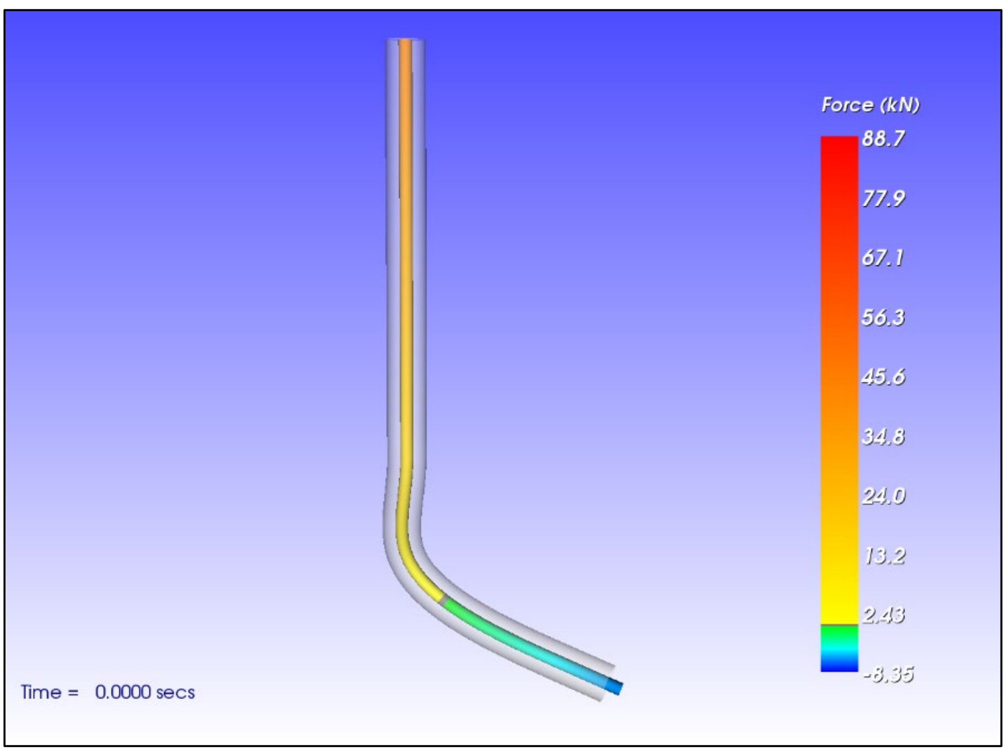

Figure 10 - Illustration of the true forces in the rod string before motion ensues.

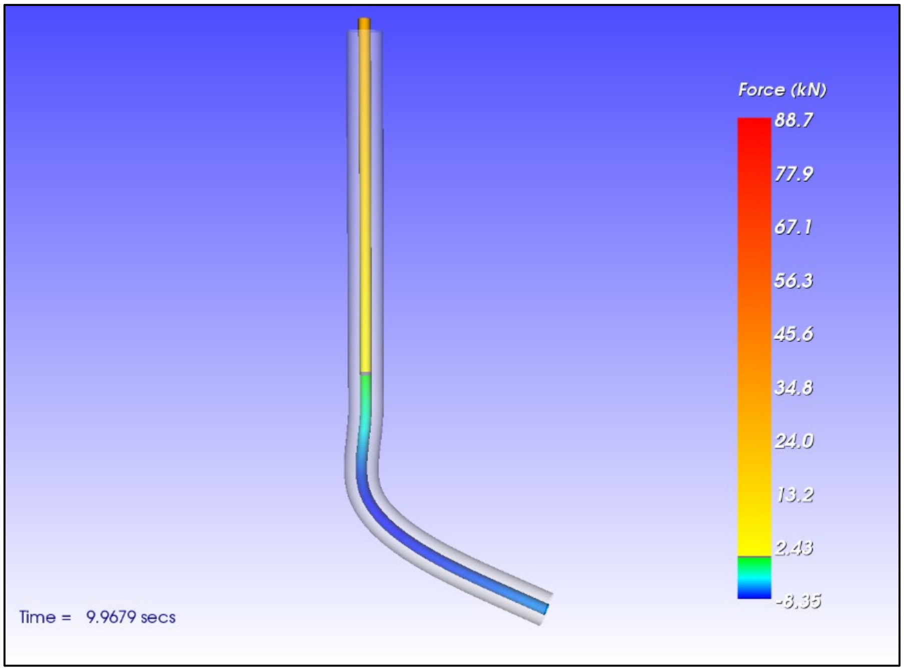

Figure 11 - The true forces in the rod string at the time station where buckling is happening above. The extent of the compressive zone is much longer than when dynamic loads alone are considered and the magnitude of the compressive force in the buckling zone is far greater.

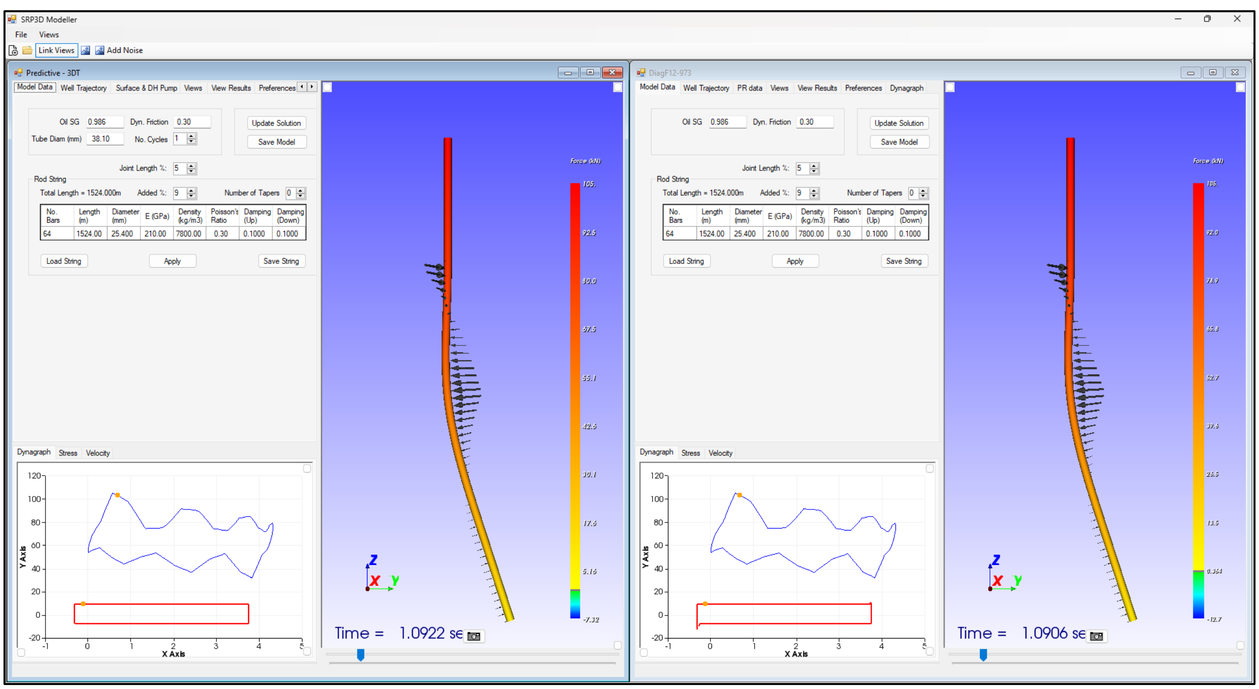

Figure 12 – The left-hand pane shows the predictive model simulation and the right-hand pane shows the application of the predictive model surface card to the diagnostic model – and the resulting down hole card, that is a close match to the predictive down hole card.

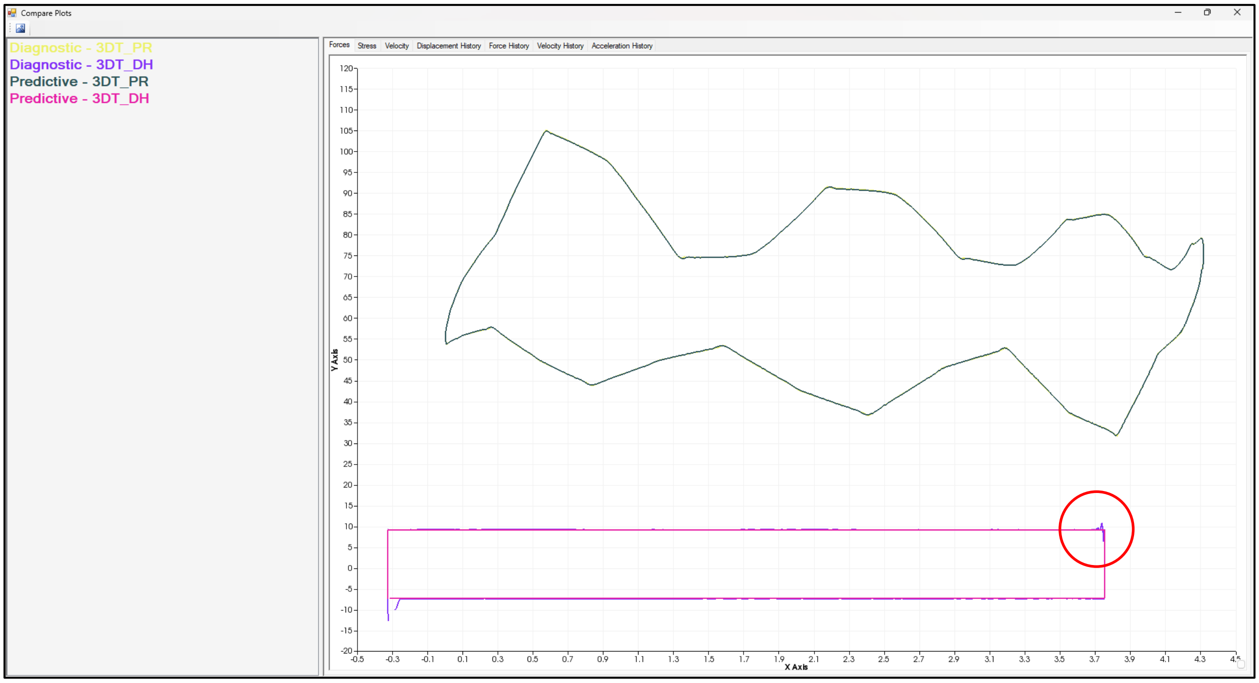

Figure 13 – The diagnostic surface and downhole cards superposed on the predictive cards. There is a very close match, with a slight instability in the diagnostic solution.

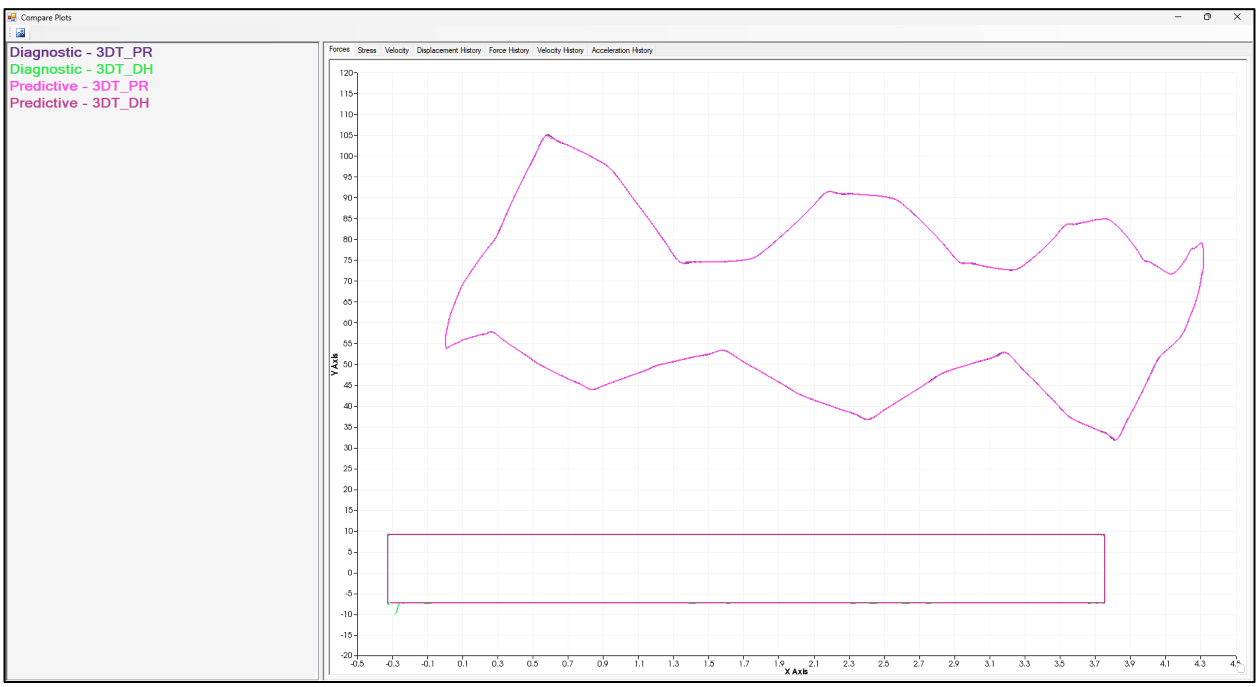

Figure 14 – Application of a case-by-case correction to the diagnostic solution corrects the instability.

Figure 15 - If the EW trajectory is used in the diagnostic model, we get significant error in the estimation of the DH card.

Figure 16 - Similarly, if the pseudo 3D “triangulated” trajectory is used in the diagnostic model, the estimation of the DH card is significantly off.

Figure 17 - If the full 3D trajectory is used it yields an excellent match.