MECHANICAL & VISCOUS FRICTION COMPARATIVE ANALYSIS OF PERMIAN AND BAKKEN WELLS: FIELD DATA

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ABSTRACT:

In sucker rod pumps, work at the surface is translated to the pump downhole using a polished rod and rod string. Three factors reduce the energy available at the pump and decrease the efficiency of the rod pump installation.

The first factor is elasticity. Due to the elastic nature of the rod string and the cyclic motion of the pumping unit, stress waves travel up and down the rod string at the speed of sound, reducing the pump stroke and the efficiency of the downhole pump.

Secondly, viscous friction issued from the produced fluids, which impart a viscous force on the outer diameter of the rod string, further dampen the rod string's movement.

Lastly, due to the deviation in a well, mechanical friction occurs when the rod string, pump or couplings come into contact with the tubing producing a normal force and drag friction that further slows down the movement of the rod string and reduce pump action.

In the great majority of models available to the industry, viscous friction is not adjusted properly, while mechanical friction is not addressed at all. In this paper, results from Liberty Lift's proprietary diagnostic model are discussed comparing the mechanical and viscous frictions in different Permian and Bakken wells.

INTRODUCTION

In Sucker Rod Pumped wells, the circular motion at the surface is translated to a vertical motion of the rod string, effectuating the pump. The movement of the rod string is impeded by three phenomena: elasticity, viscous friction, and mechanical friction.

The rod string is composed of thousands of feet of rods made of steel, fiberglass, and other material. At each stroke, the rod string lifts the weight of the rod string elements below as well as the weight of the lifted fluids. During the pumping cycle, the rods string experiences cyclic compression and tension as the rods move up and down thousands of feet. This phenomenon creates stress waves that travel up and down the rod string at the speed of sound. This is called Elasticity. This removes energy from the system as stress waves coming from two different points can coincide to create compression in the rod string and therefore buckling.

Secondly, the fluid lifted to the surface imparts a viscous force on the outer diameter of the rod string slowing down its progression. Viscous forces are proportional to the velocity of the rod string, which means that pumping fast accentuates viscous forces and introduces viscous dynamics in the downhole data, whereas pumping slow will reduce the dynamics observed within a stroke, cf. [9, 10, 14].

Finally, mechanical friction results from the lateral movement of the rod string and its contact with either the tubing, or the pump. Mechanical friction is issued from contact, see [5, 8, 9, 11]. This happens mostly due to deviation but can also happen in cases of paraffin or other solids. Mechanical friction can be seen as a pinpoint for the rod string where movement is either stopped or slowed down due to a physical barrier (i.e. the tubing, pump or paraffin).

Traditionally, the wave equation is used to calculate downhole data from surface data, see [1, 2, 3, 4, 6, 7, 10, 12, 13].

In the majority of methods available to the operator for downhole data calculation and automation hardware and software, viscous damping is a set value, where a coefficient might get adjusted whenever the field technician has time and spends time optimizing and analyzing the well. In reality, viscous damping is a dynamic quantity for two major reasons. The first reason is that as mentioned above viscous friction is proportional to the velocity of the rod string. This means that operating conditions will greatly affect the presence of viscous friction in the system. Secondly, viscous friction depends on the amount of fluids being lifted to the surface, which varies greatly during the pumping cycle. As the well pumps off, less fluids are being produced, therefore less viscous friction in the system and therefore the damping factor should be lowered. This requires constant adjustment for the downhole data to be accurate, cf. [10, 14].

With most of the industry being now satisfied with erroneous results from ill-adjusted damping factors, downhole data that is either overdamped or underdamped. In the over damped case, a loop is present on the right-hand side of downhole card, which can’t exist due to the physical constraints of the pumping unit, so the data has been altered to the point that it is now falsified. Alternatively, the other case is underdamped characterized by a fat downhole card, where the downhole card is blown up, which causes all values from fluid load, gross stroke and netstroke to be grossly distorted.

An optimally damped downhole card should ideally have a flat upstroke and flat downstroke, see [10].

In this paper, results presented in this paper show downhole data calculated with no friction adjustment, which is representative of what most of the industry has at their disposal while using manually adjusted single damping vertical hole model. These results are compared to results of the Iteration on Damping, i.e. Viscous model where only viscous friction is removed. Finally, these results are compared to the results of Liberty Lift’s Deviated model where mechanical friction is removed.

METHODS & PROCEDURES

A. Rod Pumps & Wave Equation

When the assumption is made that the rod string does not move laterally, i.e. the rod string only moves up and down and effects of deviation are neglected, the rod string can be compared to an ideal slender bar and the propagation of the stress waves becomes a one-dimensional phenomenon. Under this assumption, one can use the wave equation to model the propagation of the stress waves in the rod string, see [9, 14].

The condensed one-dimensional wave equation reads:

$$v^2 \frac{\partial^2 u}{\partial x^2} - D\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial t^2}, \tag{1}$$

where the acoustic velocity is given by: $v = \sqrt{\frac{144Eg}{\rho}}$.

The first term in the equation represents elasticity; the second term represents the viscous damping force, while the last represents the system’s acceleration.

As can be seen from the negative sign in front of the damping force, the goal of the damping term is to remove energy from the system to mimic the energy lost due to viscous forces. As mentioned, mechanical friction is ignored for this model. This model uses a finite difference method solution to the wave equation.

Viscous Damping represents energy we are removing from the wave equation which mimics the energy lost due to viscous friction during pumping. Conditions are very different between the upstroke and downstroke, i.e., due to the direction of the fluid flowing with or against the rods. The same damping factor cannot be used for both upstroke and downstroke. As the wells pumps off, viscous friction decreases, and different values for damping are needed. Therefore, a separate damping factor should be used for the upstroke than for the downstroke.

In practice, calculating damping factors is not a reliable method for great accuracy. Iterating on upstroke and downstroke damping factors is preferred and much more accurate, see [10, 14].

In this paper, results from a viscous model where an iteration on viscous damping factors are presented. More details on this method can be found in [10].

B. Mechanical Friction

Mechanical friction issues from intentional and non-intentional deviation during the drilling process. To access many of the reservoirs nowadays wells have to be drilled with a planned deviation where the well's trajectory deviates from the vertical at a “kick off point” and/ or at a lateral at the bottom of the wellbore.

In these cases, operators have at their disposal deviation surveys which can be conducted at various distance increments, called survey stations. For a long time, an industry practice was to have a deviation survey station every 100ft., however in recent years and since the dawn of deviated solutions, a preferred spacing for stations is under 25ft. with an ideal with a continuous gyroscope survey every foot.

Deviation surveys contain measured depth, the measured distance from the surface along the center line of the tubing string, the inclination which is the angle measured between the borehole direction and the vertical in degrees, and finally the azimuth, which is the angle of the borehole direction as projected to a horizontal plane and relative to due north measured in a clockwise direction.

Using a deviation survey, operators can easily calculate the path of the trajectory using several methods such as the minimum curvature method and calculate dog leg severity. Dog leg severity or DLS is a normalized estimate of the 3D curvature of the trajectory. DLS can be calculated using only inclination, but this practice does not yield accurate results in deviated wells. When DLS is calculated both azimuth and inclination angle should be considered to measure the tortuosity of the wellbore, cf. [15].

While in vertical wells, the wave equation is enough to reliably and accurately calculate downhole data, this is not the case in deviated wells. The magnitude of the mechanical friction forces is too great to ignore. Mechanical friction depends on the normal force and the friction coefficient between the two objects in contact, in this case, the rods and the tubing.

Mechanical friction acts in the opposite direction of the motion, removing energy from the system. While viscous friction is proportional to the velocity of the rod string, mechanical friction is not.

The severity of the mechanical friction present in a well depends on the amount of deviation, the dog leg severity mentioned above but also depends on the depth of the kick off point or point of deviation. If a deviation event (kick off point or pinch point) happens deep in the wellbore, the consequences of such an event will be less severe than if that event were to happen near the top of the rod string, let's say the first 3000-4000 ft. The explanation for that is very simple; each rod element carries the weight of all the elements below as well as the weight of the fluid being lifted to the surface.

This explains why, if the deviation event happens at the top of the well, the effect of the deviation on the loading and drag of the rod string will be much larger.

Liberty Lift has developed a deviated diagnostic method, which removes mechanical friction from the downhole data. Results are presented below.

C. Key control parameters

Key control parameters must be extracted from downhole position and load data to optimize and efficiently control a sucker rod-pumped installation.

These key control parameters include:

- Fluid load - F0 – vertical span of the downhole card
- Net stroke – NS – refers to the portion of the plunger travel that contains fluid, i.e. pump fillage PF
- Traveling valve opening and closing
- Standing valve opening and closing

The above quantities are essential in inferred production calculation as well as slippage and oil shrinkage calculation. Inferred production is an important KPI to measure efficiency of installation.

D. Fluid Load, Fluid Level and Pump Intake Pressure calculation

Fluid load ideally represents the vertical span of the card. However, when friction is present in the well and using a model that doesn't properly account for the viscous and mechanical friction forces, fluid load can become very difficult to calculate as it is obscured by the friction present in the downhole card.

Fluid load, denoted F0, is calculated to be the difference between F0up and F0dn, which in a frictionless card would correspond to the upstroke and downstroke load.

Fluid load is used in important calculations, in particular fluid level and pump intake pressure calculations.

If the fluid load is not calculated properly, it could lead to erroneous values for the fluid level such as a negative fluid level, which is of course impossible.

Fluid level and pump intake pressure can be used to optimize production on a rod pump well by assessing whether the pumping unit's speed can be increased safely or to push production capability on a unit. Using an accurate fluid level, the user can verify whether the rod pump system is experiencing pump off or gas interference for instance. If the former, then the pumping unit should be slowed down or stopped, if the latter, it is possible to pump through the gas, draw down the well and get more production.

This is only possible if the value of the fluid level or pump intake pressure is accurate, in other words, if the calculated fluid load value is accurate and representative of the well's condition. If the fluid load is bigger than actual, this will lead to a negative fluid level.

E. Inferred Production Calculation

Inferred production allows the operator to estimate how much fluid and gas is being produced by the well based on the pump fillage of the downhole data, oil shrinkage and oil slippage. Accurate calculation of pump fillage is critical for optimal results and efficiency of pumping operations. Pump fillage can be difficult to calculate due to the many different downhole conditions that can happen in the well.

Correct calculation of valve openings and closings is also essential to the accurate calculation of the netstroke and the proper estimation of slippage but can be very challenging to calculate correctly due to the dynamic nature of the DHC. Pump fillage and netstroke are moving targets as the well cycles from full to pumped off conditions.

Inferred Production is calculated using the following equation:

$$Inferred\ Production = 0.1166 * SPM * NS * \ PlgDiam^2, \qquad (2)$$

Where SPM represents the pumping unit speed, strokes per minute, NS is the netstroke, and $PlgDiam$ is the diameter of the plunger.

In the next section, results are presented and discussed.

RESULTS

In the following results, three models are compared.

The first model is the full-friction model, meaning that nothing was removed from the system to account for the energy lost to friction, i.e. no viscous damping or mechanical friction was removed from the downhole card.

The second model is the viscous damping model which removes friction from viscous forces from the wave equation. This is the traditional vertical hole 1-dimensional damped wave equation with automatic iteration on dual damping factors as described in [10].

The final model is a deviated diagnostic model which removes all friction from both viscous and mechanical origin.

1) Well 1

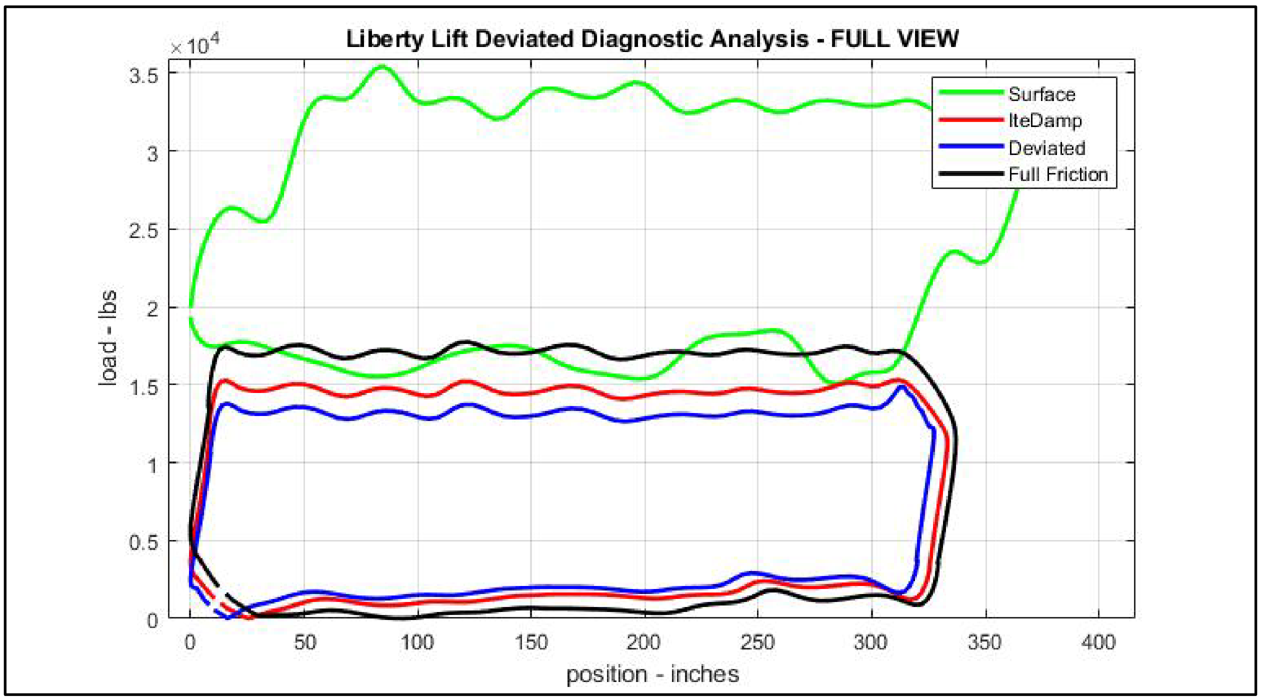

Figure 1: Well 1 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	337	328	N/A	16932	332	16600	N/A
Viscous Damping	333	325	3	14398	1270	13128	3472
Deviated	325	318	10	12643	2048	10595	6005

Table 1: Well 1 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 1 has a pump depth of 8300 ft and a plunger diameter of 2.0 inches. The pumping unit is a long stroke unit with a stroke length of 366 inches and runs at 3.59 SPM.

The downhole cards displayed in Figure 1 show a mostly full plunger and a pump fillage close to 100. There are many undulations in the downhole card, which appear to be on viscous nature since they are present at both the start of the upstroke and the start of the downstroke.

In Figure 1, the surface card is displayed in green. In black, the full friction card is displayed. Full friction means that no viscous friction or mechanical friction was removed when solving the wave equation. In red, the viscous damping model card is displayed. The viscous damping model means that only friction of viscous nature was removed from the wave equation when calculating downhole data. Finally, in blue, results of the deviated model are displayed. In the deviated model, mechanical friction is removed.

The full friction card is longer and larger than the other two cards. The viscous damping card is smaller and shorter with the deviated model card smaller and shorter still. This is because the presence of friction expands the downhole card during the solving of the wave equation because the wave equation attributes any unclaimed friction to the pump. The difference in netstroke from the viscous damping card to the full friction card is 3 inches while the difference between the deviated model card and the full friction card is 10 inches.

Table 1 shows the measured gross stroke, netstroke, F0up, F0down and calculated difference in netstroke with the full friction model, the calculated fluid load and the difference in fluid load of the viscous damping and deviated model compared to the full friction model.

For Well 1 the gross stroke for the full friction model is 337 inches, compared to a shorter gross stroke of 333 for viscous and 325 for deviated. The netstroke for the full friction model is 328 inches compared to 325 and 318 for the viscous and deviated model. This means that there is a 3-inch difference in netstroke between viscous damping and deviated and a staggering 10 inches difference between the deviated model and the full friction model.

This might not look like a big difference but considering wells can run 24 hours per day, sometimes with no idle time this equates to a very significant difference in production.

For this well, at a speed of 3.59 SPM and a plunger diameter of 2 inches, the inferred production calculated from the full friction card can be calculated from equation (2) and is equal to:

$$Q_{FF} = 0.1166 * 3.59 * 328 * 2^2 = 549.19\, BBls.$$

However, if we compute the inferred production this time with the viscous damping netstroke, we get:

$$Q_V = 0.1166 * 3.59 * 325 * 4 = 544.17\, BBls.$$

Finally, if we compute the inferred production with the deviated model netstroke, we get:

$$Q_D = 0.1166 * 3.59 * 318 * 4 = 532.45\, BBls.$$

This means that if an operator is not accounting for viscous friction on this well, they will overestimate the production by 5 BBls per day and if the operator is not accounting for deviation and the mechanical friction that it incurs, they will overestimate the production by 17 BBls. per day. The differences in inferred production might not seem like a lot but this is a daily average, over the course of a month this equates to an overestimation of 150 BBls. in the case of the viscous friction model or 510 BBls. in the case of the deviated model.

Similarly, fluid load is an important quantity for the optimization and control of sucker rod pumps.

As mentioned above, fluid load is crucial in the calculation of pump intake pressure and fluid level and many other important calculations.

From Table 1, the fluid load in the full friction model is 16600 lbs., while the fluid load for the viscous damping model is 13128 lbs. and 10595 lbs. for the deviated model. In the case of the full friction model, the fluid load is overestimated by 3472 lbs. while for the deviated model, the fluid load is overestimated by a staggering 6005 lbs.

2) Well 2

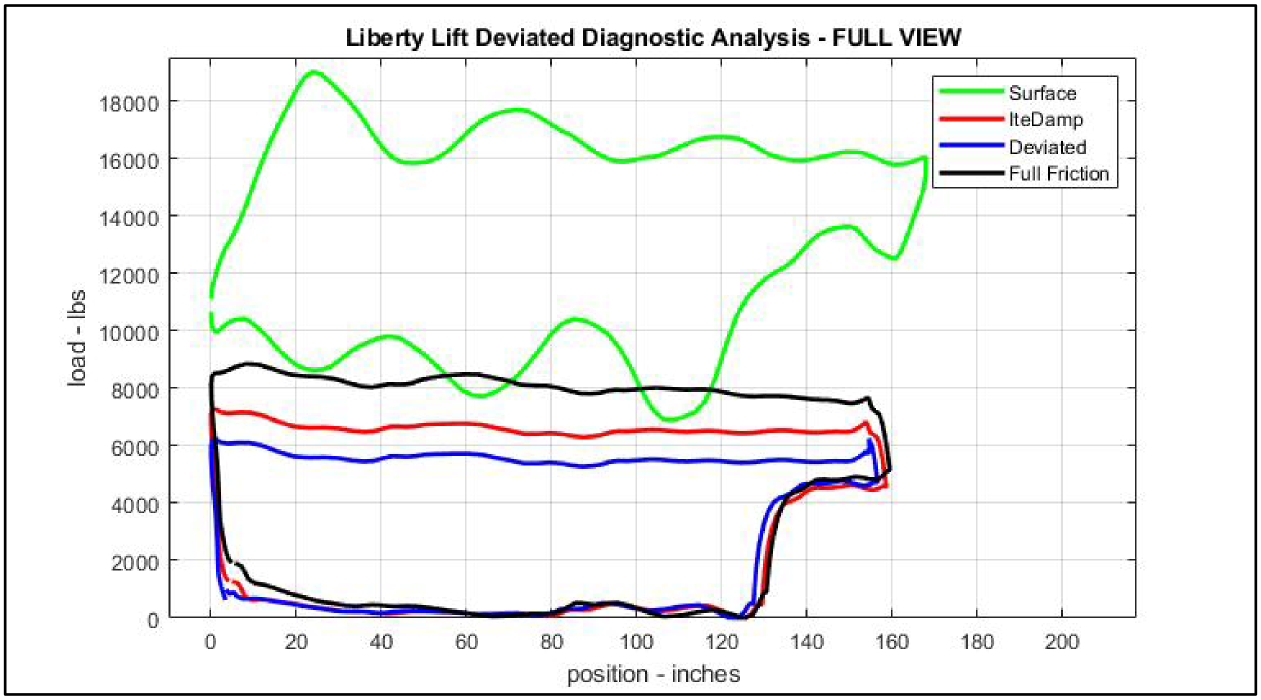

Figure 2: Well 2 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	159	130	N/A	8013	255	7758	N/A
Viscous Damping	158	129	1	6832	204	6628	1130
Deviated	156	127	3	5799	255	5544	2214

Table 2: Well 2 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 2 has a pump depth of 8000 ft, a stroke length of 168 inches and runs at 3.69 SPM. The plunger diameter for this well is 1.75 inches.

The downhole cards displayed in Figure 2 show a pump off card with incomplete fillage of around 80%. There doesn't seem to be any other on-going downhole conditions in the example.

For Well 2 the gross stroke for the full friction model is 159 inches, compared to a shorter gross stroke of 158 for viscous and 156 for deviated. The netstroke for the full friction model is 130 inches compared to 129 and 127 for the viscous and deviated model. This means that there is a 1-inch difference in netstroke between viscous damping and deviated and a 3-inches difference between the deviated model and the full friction model.

Using the same logic as for the previous example, we can compare the inferred production calculated using the full friction model versus the inferred production calculated using the viscous damping and the deviated model.

In this case, we get $Q_{FF} = 171.29\ BBls.$, $Q_V = 169.97\ BBls.$ And $Q_D = 167.34\ BBls.$. Over the course of a month, this equals to a difference of 60 barrels for the viscous case and 120 barrels for the deviated case.

From Table 2, the fluid load in the full friction model is 7758 lbs., while the fluid load for the viscous damping model is 6628 lbs. and 5544 lbs. for the deviated model. Furthermore, the difference in fluid load is 1130 lbs. for the viscous model and 2214 lbs. for the deviated model.

3) Well 3

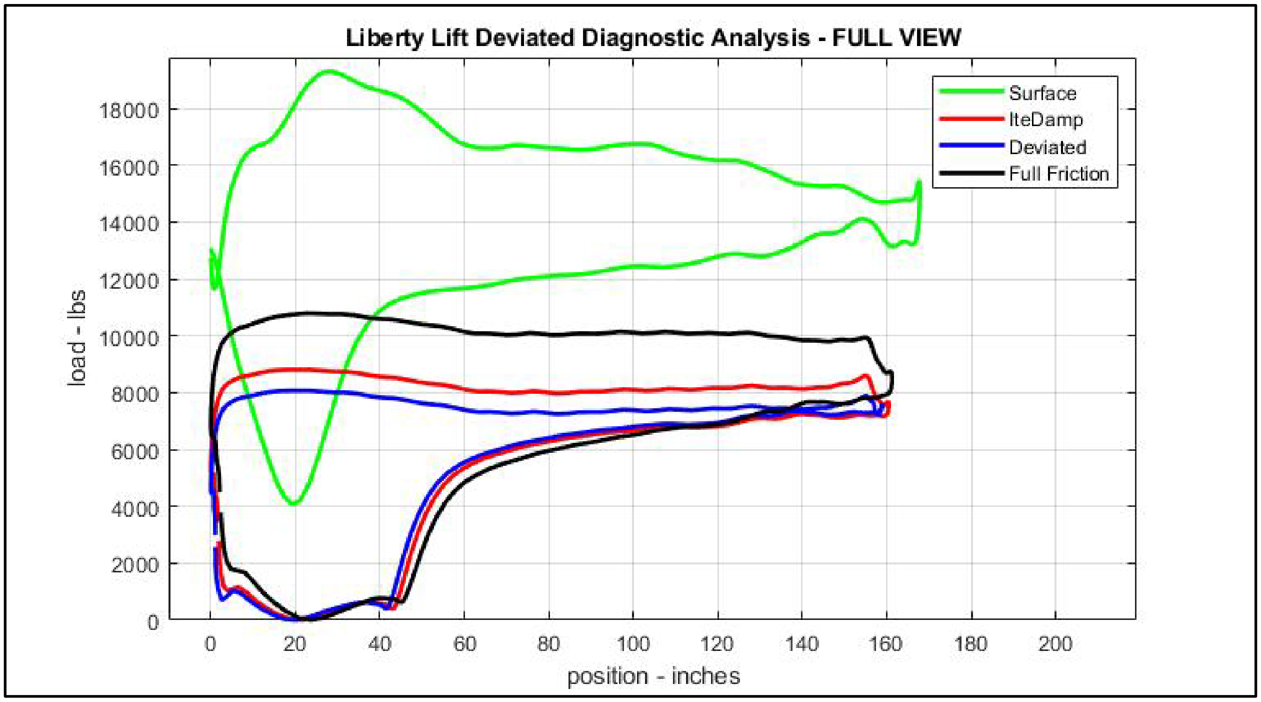

Figure 3: Well 3 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	161	48	N/A	10080	772	9308	N/A
Viscous Damping	160	47	1	8035	541	7494	1814
Deviated	156	45	3	7316	540	6776	2532

Table 3: Well 3 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 3 has a pump depth of 4408 ft, a stroke length of 168 inches and runs at 7.34 SPM. The plunger diameter on this well is 2 inches.

As can be seen from Figure 3, the downhole cards in this case exhibit incomplete fillage due to pump off and some mild gas interference. This is inferred from the sloped decrease after the top of stroke where the loads slowly decrease at an angle before the transfer point. A rounded edge can be seen at the beginning of the upstroke reflective of gas compression.

For Well 3 the gross stroke for the full friction model is 161 inches, compared to a shorter gross stroke of 160 for viscous and 156 for deviated. The netstroke for the full friction model is 48 inches compared to 47 and 45 for the viscous and deviated model. This means that there is a 1-inch difference in netstroke between viscous damping and deviated and a 3-inches difference between the deviated model and the full friction model.

In this case, we get $Q_{FF} = 164.32\ BBls.$, $Q_V = 160.89\ BBls.$ And $Q_D = 154.05\ BBls.$. Over the course of a month, this equals to a difference of 120 barrels for the viscous case and 300 barrels for the deviated case.

From Table 3, the fluid load in the full friction model is 9308 lbs., while the fluid load for the viscous damping model is 7494 lbs. and 6776 lbs. for the deviated model. The difference in fluid load is 1814 lbs. for the viscous model and 2532 lbs. for the deviated model.

4) Well 4

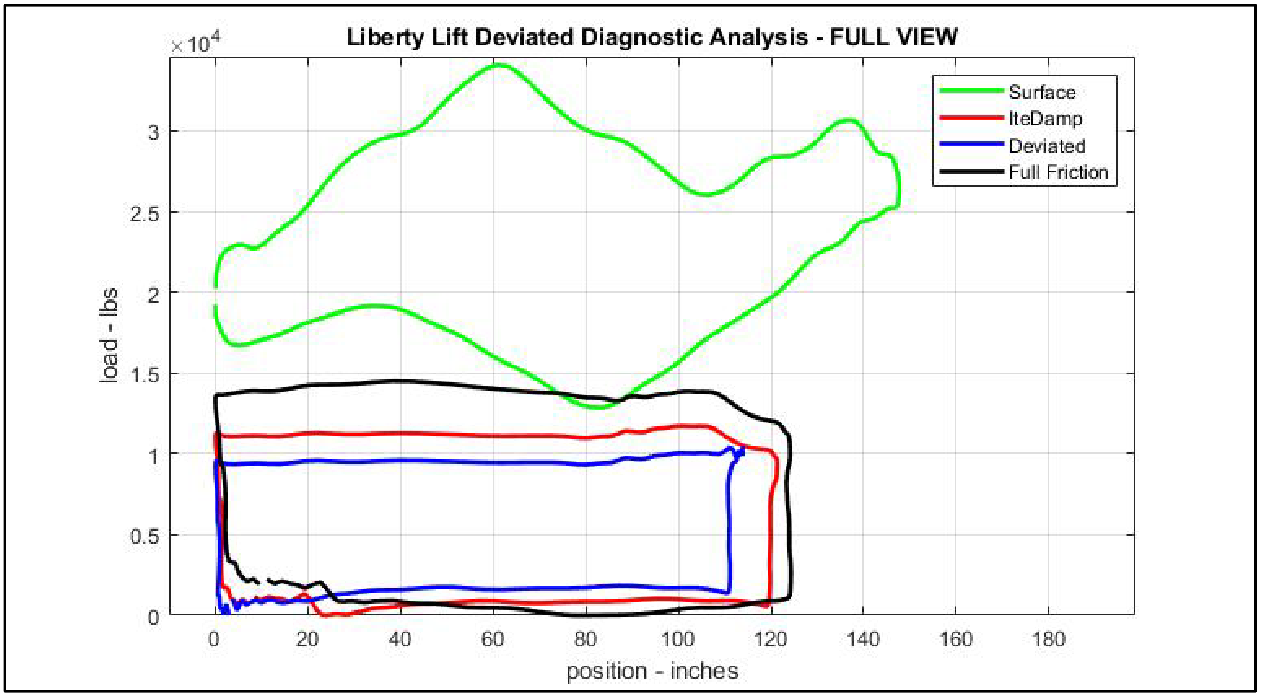

Figure 4: Well 4 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	124	123	N/A	13476	80	13393	N/A
Viscous Damping	121	119	4	10960	850	10110	3283
Deviated	113	110	13	9323	1705	7618	5775

Table 4: Well 4 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 4 has a pump depth of 7925 feet with a stroke length of 147 inches and is running at 5.73 SPM. The diameter of the plunger on this well is 2 inches.

The downhole cards displayed in Figure 4 show a full pump with some sort of anomaly on the top right and bottom left corner. This could be stuffing box friction. One can observe that the stuffing box friction has been removed using the deviated model.

For Well 4 the gross stroke for the full friction model is 124 inches, compared to a shorter gross stroke of 121 for viscous and 113 for deviated. The netstroke for the full friction model is 123 inches compared to

119 and 110 for the viscous and deviated model. This means that there is a 4-inch difference in netstroke between viscous damping and deviated and an impressive 13-inches difference between the deviated model and the full friction model.

Using the same logic as for the previous example, we can compare the inferred production calculated using the full friction model versus the inferred production calculated using the viscous damping and the deviated model.

In this case, we get $Q_{FF} = 328.71\ BBls.$, $Q_V = 318.02\ BBls.$ And $Q_D = 293.97\ BBls.$. Over the course of a month, this equals to a difference of 300 barrels for the viscous case and 1042 barrels for the deviated case.

From Table 4, the fluid load in the full friction model is 13393 lbs., while the fluid load for the viscous damping model is 10110 lbs. and 7618 lbs. for the deviated model. The difference in fluid load is 3283 lbs. for the viscous model and 5775 lbs. for the deviated model.

5) Well 5

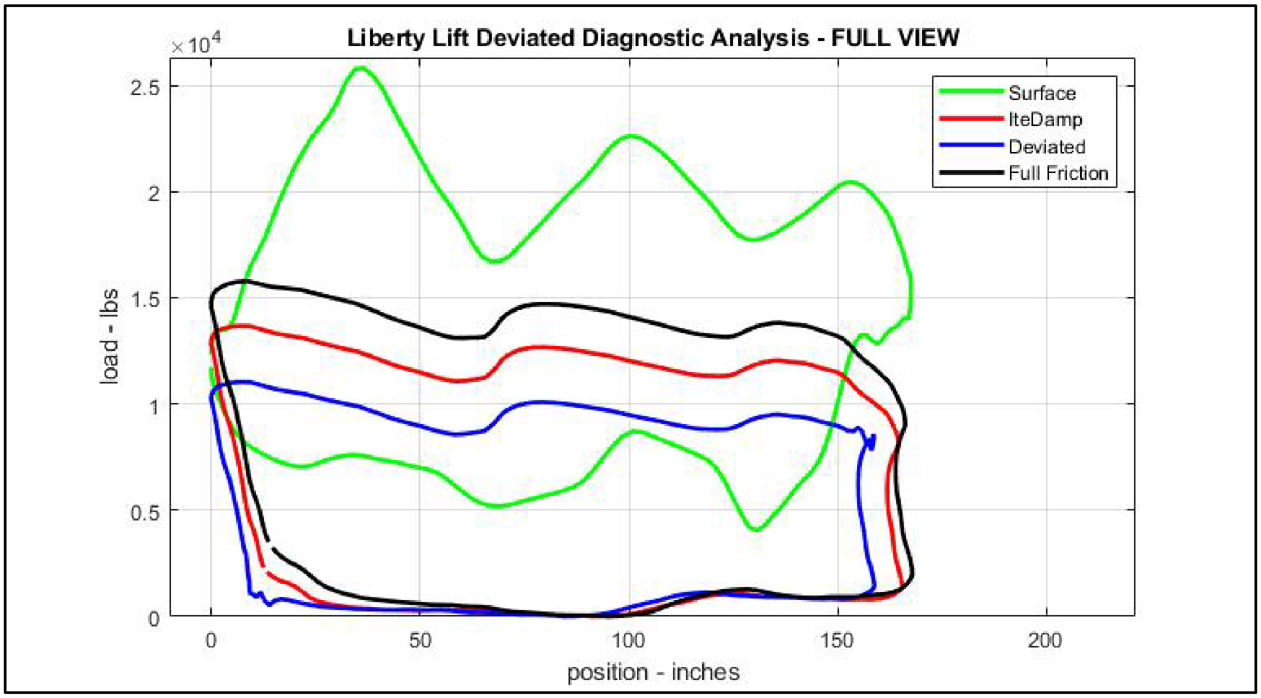

Figure 5: Well 5 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	168	166	N/A	13974	32	13942	N/A
Viscous Damping	164	163	3	12033	32	12001	1941
Deviated	158	157	9	9482	261	9221	4721

Table 5: Well 5 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 5 has a pump depth of 4765 feet and a stroke length of 168 inches.

The well is running at 6.98 SPM and has a plunger diameter of 2 inches.

The downhole cards displayed in Figure 5 show a near full downhole card with a lot of waves or dynamics on the upstroke. One can observe that the deviated card does appear more rectangular than the other two cards, as if the model offers better definition.

For Well 5 the gross stroke for the full friction model is 168 inches, compared to a shorter gross stroke of 164 for viscous and 158 for deviated. The netstroke for the full friction model is 166 inches compared to 163 and 157 for the viscous and deviated model. This means that there is a 3-inch difference in netstroke between viscous damping and deviated and an impressive 9-inches difference between the deviated model and the full friction model.

In this case, we get $Q_{FF} = 540.40\ BBls.$, $Q_V = 530.64\ BBls.$ And $Q_D = 511.10\ BBls.$. Over the course of a month, this equals to a difference of 300 barrels for the viscous case and 870 barrels for the deviated case.

From Table 5, the fluid load in the full friction model is 13942 lbs., while the fluid load for the viscous damping model is 12001 lbs. and 9221 lbs. for the deviated model. Furthermore, the difference in fluid load is 1941 lbs. for the viscous model and 4721 lbs. for the deviated model.

6) Well 6

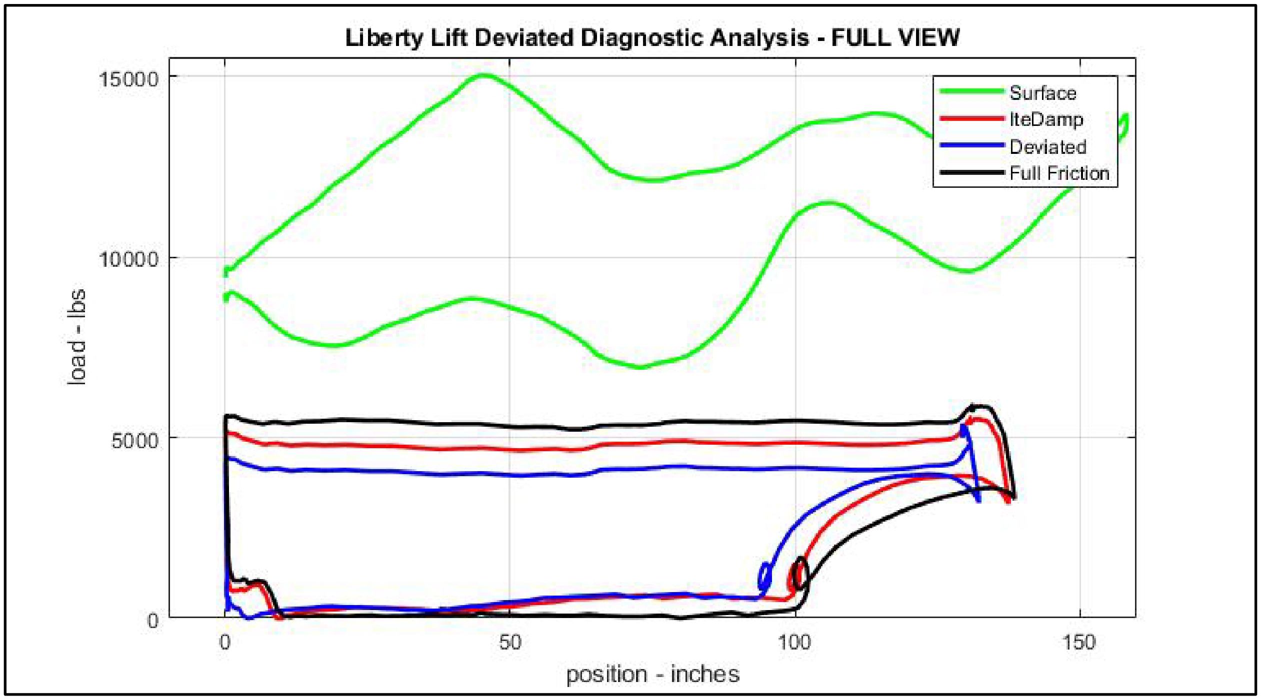

Figure 6: Well 6 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	138	103	N/A	5287	99	5188	N/A
Viscous Damping	137	101	2	4674	318	4356	832
Deviated	132	95	8	3976	454	3522	1666

Table 6: Well 6 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 6 has a pump depth of 6650 feet and a stroke length of 168.50 inches. The unit is running at 3.89 SPM and has a plunger diameter of 1.50 inches.

The downhole cards displayed in Figure 6 show incomplete fillage due both to pump off and mild gas interference, as is evident from the pump fillage of about 74% but the absence of the gas compression curve at the beginning of the upstroke.

For Well 6 the gross stroke for the full friction model is 138 inches, compared to a shorter gross stroke of 137 for viscous and 132 for deviated. The netstroke for the full friction model is 103 inches compared to 101 and 95 for the viscous and deviated model. This means that there is a 2-inch difference in netstroke between viscous damping and deviated and an impressive 8-inches difference between the deviated model and the full friction model.

In this case, we get $Q_{FF} = 107.81\ BBls.$, $Q_V = 105.72\ BBls.$ And $Q_D = 99.44\ BBls.$. Over the course of a month, this equals to a difference of 60 barrels for the viscous case and 240 barrels for the deviated case.

From Table 6, the fluid load in the full friction model is 5188 lbs., while the fluid load for the viscous damping model is 4356 lbs. and 3522 lbs. for the deviated model. The difference in fluid load is 832 lbs. for the viscous model and 1666 lbs. for the deviated model.

7) Well 7

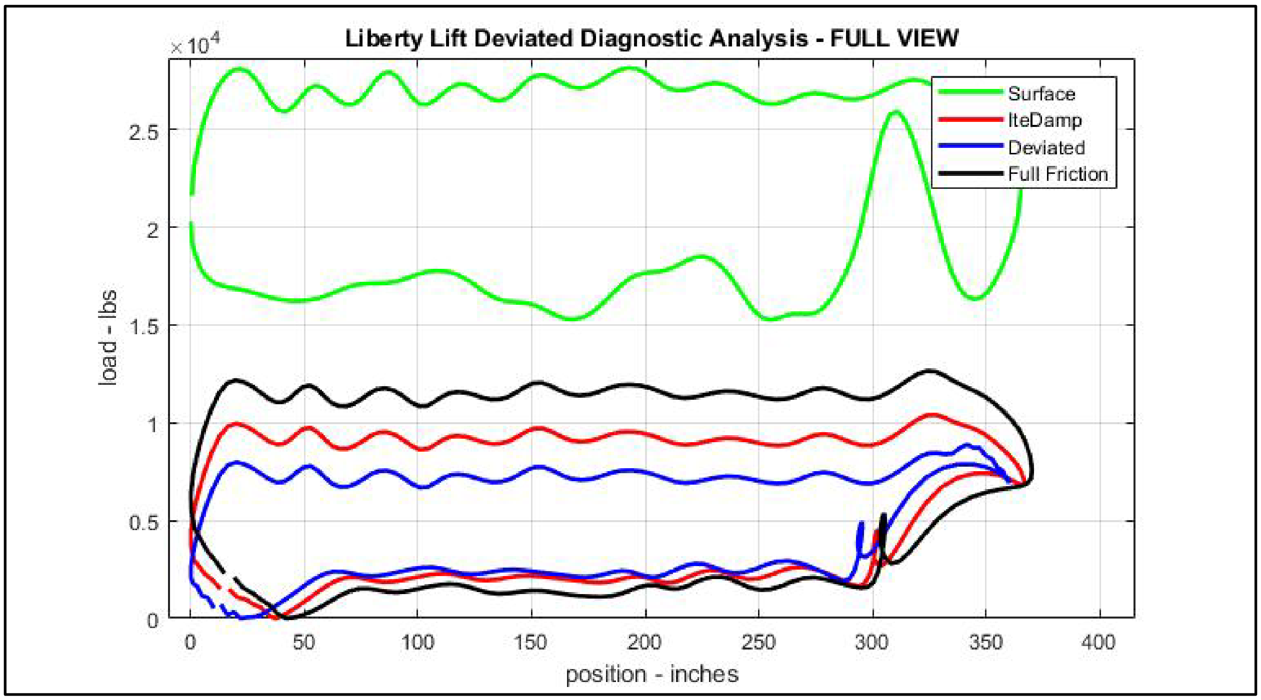

Figure 7: Well 7 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	370	311	N/A	11953	1441	10512	N/A
Viscous Damping	366	307	4	9481	2147	7334	3178
Deviated	359	300	11	7510	2147	5363	5149

Table 7: Well 7 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 7 has a pump depth of 8200 feet and a stroke length of 366 inches. The unit operates at 3.95 SPM and the plunger diameter is 2 inches.

The downhole cards displayed in Figure 7 show incomplete fillage with gas interference. There are a lot of fluid dynamics in this well as can be soon from the stress waves visible on the card. This is evident as the waves are more prominent towards the start of the upstroke and the start of the downstroke that dissipate as we reach either the top of stroke or the bottom of stroke.

The bottom left corner and top right corner show diagonal flat area, which is indicative of the speed change on a long stroke unit as the pumping unit slows down towards top of stroke and bottom of stroke. This is due to inertia of the rods as the unit tries to slow down around the corners.

After the top of stroke, near the traveling valve opening, a vertical loop in the cards indicates a possible sinker bar reflection.

For Well 7 the gross stroke for the full friction model is 370 inches, compared to a shorter gross stroke of 366 for viscous and 359 for deviated. The netstroke for the full friction model is 311 inches compared to 307 and 300 for the viscous and deviated model. This means that there is a 4-inch difference in netstroke between viscous damping and deviated and an impressive 11-inches difference between the deviated model and the full friction model.

In this case, we get $Q_{FF} = 572.94\ BBls.$, $Q_V = 565.57\ BBls.$ And $Q_D = 552.68\ BBls.$. Over the course of a month, this equals to a difference of 210 barrels for the viscous case and 600 barrels for the deviated case.

From Table 7, the fluid load in the full friction model is 10512 lbs., while the fluid load for the viscous damping model is 7334 lbs. and 5363 lbs. for the deviated model. The difference in fluid load is 3178 lbs. for the viscous model and 5149 lbs. for the deviated model.

8) Well 8

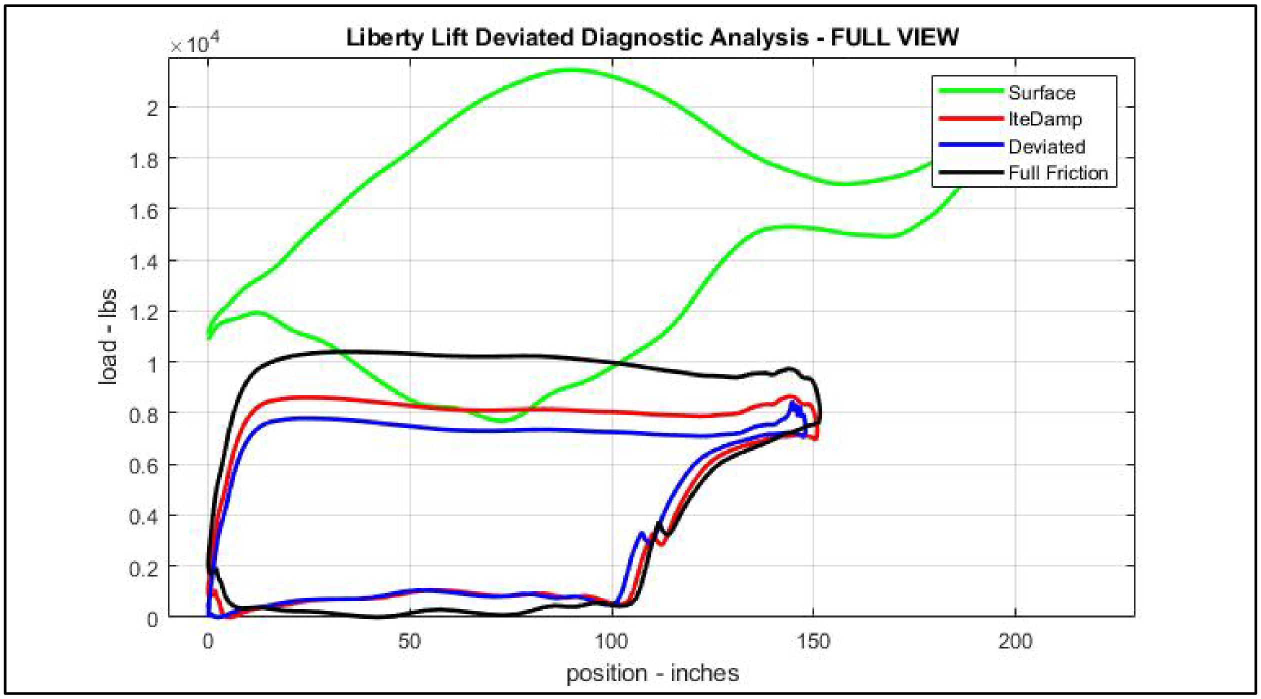

Figure 8: Well 8 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	151	108	N/A	10217	178	10039	N/A
Viscous Damping	150	106	2	8107	927	7180	2859
Deviated	147	103	5	7306	912	6394	3645

Table 8: Well 8 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 8 has a pump depth of 6365 feet and a stroke length of 192 inches. The unit is run at 5.12 SPM and has a plunger diameter of 2 inches.

The downhole cards in Figure 8 show incomplete fillage due to gas interference and possible pump off. The gas interference can be seen through the sloped decrease after the top of stroke and the rounded top left corner due to gas compression.

For Well 8, the gross stroke for the full friction model is 151 inches, compared to a shorter gross stroke of 150 inches for the viscous model and 147 inches for the deviated model. The netstroke for the full friction model is 108 inches compared to 106 inches and 103 inches for the viscous damping model and deviated model. This means that there is a 2-inch difference in netstroke between the viscous damping model and the full friction model and a 5-inch difference between the deviated model and the full friction.

In this case, we get $Q_{FF} = 257.90\ BBls.$, $Q_V = 253.12\ BBls.$ And $Q_D = 245.96\ BBls.$. Over the course of a month, this is equivalent to a difference of 120 barrels for the viscous case and 360 barrels for the deviated case.

From Table 8, the fluid load for the full friction model is 10039 lbs., while the fluid load for the viscous damping model is 7180 lbs. and 6394 lbs. for the deviated model. The difference in fluid load of 2859 lbs. for the viscous model and 3645 lbs. for the deviated model.

9) Well 9

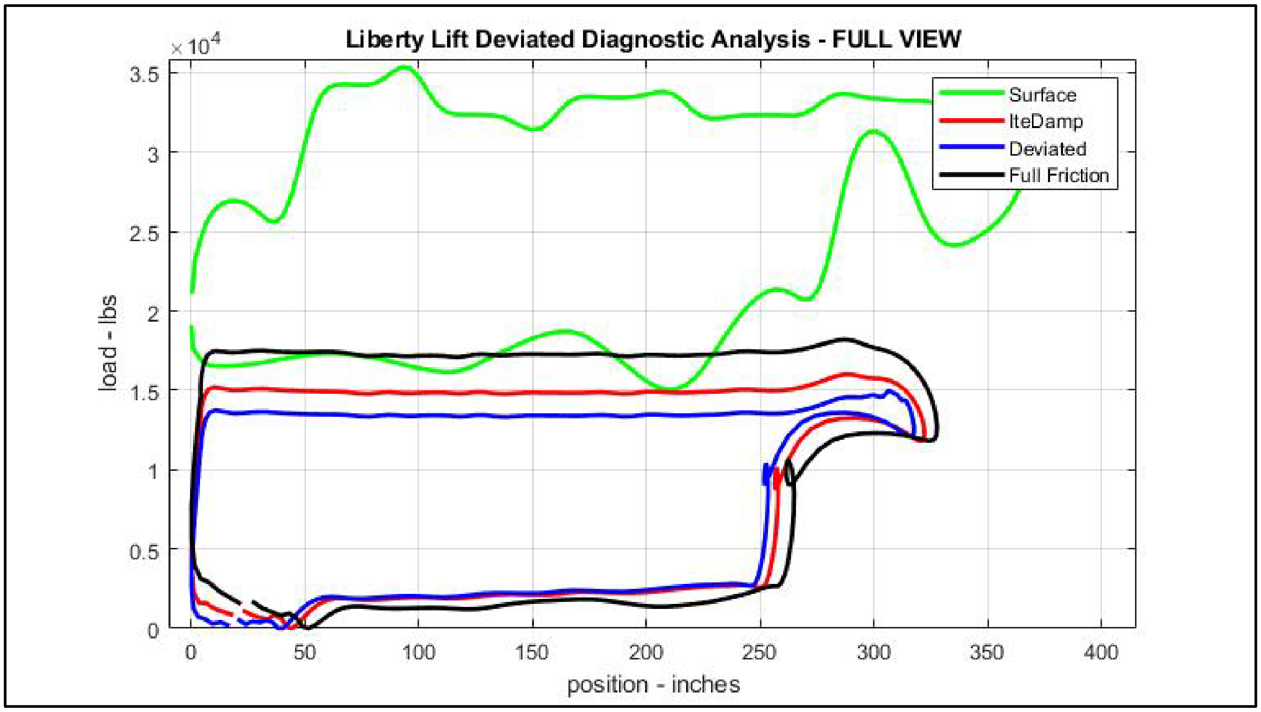

Figure 9: Well 9 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	327	260	N/A	17275	1730	15545	N/A
Viscous Damping	322	253	7	14853	2109	12744	2801
Deviated	317	249	11	13412	2204	11208	4337

Table 9: Well 9 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 9 has a pump depth of 9000 feet and a stroke length of 366 inches. The pumping unit is operated at 3.54 SPM and has a plunger diameter of 2 inches.

As can be seen by Figure 9, the downhole cards show incomplete fillage due to pump off. The rounded nose and flat diagonal area on the bottom left corner are due to rod dynamics and inertia due to the VSD slowing down the pumping unit as the unit approaches top of stroke and bottom of stroke.

For Well 9, the gross stroke for the full friction model is 327 inches, compared to a shorter gross stroke of 322 inches for the viscous model and 317 inches for the deviated model. The netstroke for the full friction model is 260 inches compared to 253 inches and 249 inches for the viscous damping model and deviated model. This means that there is a 7-inch difference in netstroke between the viscous damping model and the full friction model and a 11-inch difference between the deviated model and the full friction.

In this case, we get $Q_{FF} = 429.27\ BBls.$, $Q_V = 417.71\ BBls.$ And $Q_D = 411.11\ BBls.$. Over the course of a month, this is equivalent to a difference of 360 barrels for the viscous case and 540 barrels for the deviated case.

From Table 8, the fluid load for the full friction model is 15545 lbs., while the fluid load for the viscous damping model is 12744 lbs. and 11208 lbs. for the deviated model. The difference in fluid load of 2801 lbs. for the viscous model and 4337 lbs. for the deviated model.

10) Well 10

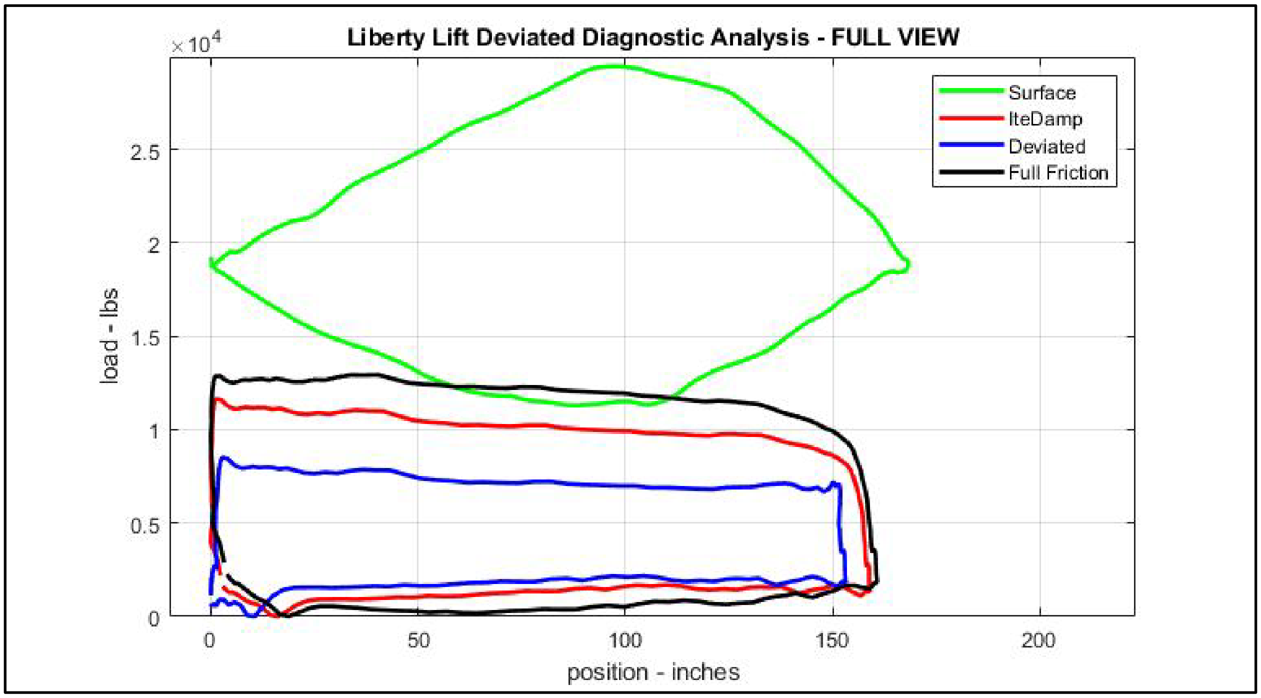

Figure 10: Well 10 Results – Surface card (green), full friction downhole card (FF) (black), viscous damping downhole card (red) and deviated downhole card (blue).

Method	Gross Stroke (in)	Net Stroke (in)	Diff NS with FF (in)	F0up (lbs.)	F0dn (lbs.)	Fluid Load F0 (lbs.)	Diff F0 with FF (lbs.)
Full Friction (FF)	160	160	N/A	12276	371	11905	N/A
Viscous Damping	158	158	2	10240	1344	8896	3009
Deviated	153	153	7	7225	1995	5230	6675

Table 10: Well 10 - Key parameters gross stroke, net stroke and fluid load comparison for full friction model (FF) vs. viscous damping model vs. deviated model.

Well 10 has a pump depth of 8761 feet with a stroke length of 162 inches. The pumping unit is operated at 6.59 SPM and has a plunger diameter of 1.75 inches.

As can be seen in Figure 10, the downhole cards are indicative of deep deviation, as characterized by their fat and rounded appearance at the top of stroke. It's important to notice that the deviated model completely removed the effects of deep deviation to produce a more rectangular and rectilinear card.

For Well 10, the gross stroke for the full friction model is 160 inches, compared to a shorter gross stroke of 158 inches for the viscous model and 153 inches for the deviated model. In this example the netstroke is equal to the gross stroke as there is no incomplete fillage and a full pump. This means that there is a 2-inch difference in netstroke between the viscous damping model and the full friction model and a 7-inch difference between the deviated model and the full friction.

In this case, we get $Q_{FF} = 376.51\ BBls.$, $Q_V = 371.80\ BBls.$ And $Q_D = 360.04\ BBls.$. Over the course of a month, this is equivalent to a difference of 150 barrels for the viscous case and 480 barrels for the deviated case.

From Table 8, the fluid load for the full friction model is 11905 lbs., while the fluid load for the viscous damping model is 8896 lbs. and 5230 lbs. for the deviated model. The difference in fluid load of 3009 lbs. for the viscous model and 6675 lbs. for the deviated model.

DISCUSSION

In all the examples presented above, the results of three models are shown.

The oil and gas industry does a poor job of taking friction into consideration when calculating downhole data. Firstly, the majority of the industry still uses a vertical hole model with a manually adjusted damping factor for both the upstroke and the downstroke. This type of model produces one of two results: an overdamped card where the downhole data has been falsified, see [10], or an underdamped card similar to the full friction model depicted in the results above.

The viscous model presented above uses a dual iteration on viscous damping to remove the correct amount of energy from the wave equation to mimic the energy lost to viscous friction during the pumping cycle. This method, however, completely neglects the presence of mechanical friction.

The third method presented removes both the viscous and mechanical friction from the downhole data.

Inferred production as mentioned above is used by operators to keep track of the production for any given well at any given time. The above examples show that it is not only possible but very likely that many operators are constantly overestimating their inferred production unless they are using a deviated diagnostic model. This leads to confusion when the volume in the tanks does not match the volume expected to come out of the well through the controller's inferred production calculation.

Also, how can one truly optimize a well when the estimation of how much a well makes is erroneous?

According to Well 4, the worst-case scenario would be an over estimation of 1042 barrels a month, which equates to $72,940 of over estimated revenue!

Similarly for the fluid load, as can be seen by the results above, the actual fluid load can be vastly different from the calculated fluid load when using an underdamped card. This means that the well cannot be optimized, the well cannot be drawn down and ultimately potential production is left behind. From the results above, Well 10 shows that the actual fluid load could be around 6675 lbs. less if using a full friction model compared to a vertical model with inadequately small damping factors.

CONCLUSIONS

Properly adjusting the viscous damping factors can have a big impact on properly calculating production rate and estimating energy lost to viscous forces. As the pumping speed increases, it becomes more and more important to properly account for the viscous friction as viscous friction is proportional to the velocity of the rod string.

Incorrectly damped downhole data cannot yield correct control variables and can compromise the efficiency and return on investment for an installation.

A vertical hole model is ill equipped to handle the friction present in deviated wells. To correctly calculate downhole data in deviated a deviated diagnostic model is needed. Downhole data calculated using a deviated diagnostic model produces downhole data free of any extra friction and enables true optimization of the rod pump installation and appropriate and safe drawdown of the well.

If the fluid load is over or under-estimated, fluid level calculations will be wrong. Erroneous fluid level estimates can cause the operator to mis-operate the well and lose potential production. As a well is pumped faster, any discrepancy or error in calculating downhole data such as under or under-estimating friction will have a snowball effect on production rate, horsepower calculation and many other calculations central to well optimization.

REFERENCES

1. Ehimeakhe, V.: “Comparative Study of Downhole Cards Using Modified Everitt-Jennings Method and Gibbs Method”, Southwestern Petroleum Short Course 2010.
2. Everitt, T. A. and Jennings, J. W.: “An Improved Finite-Difference Calculation of Downhole Dynamometer Cards for Sucker-Rod Pumps,” paper SPE 18189 presented at the 63rd Annual Technical Conference and Exhibition, 1988.
3. Gibbs, S. G., and Neely, A. B.: “Computer Diagnosis of Down-Hole Conditions in Sucker Rod Pumping Wells,” JPT (Jan. 1996) 91-98; *Trans.*, AIME,237
4. Gibbs, S. G.: “A Review of Methods for Design and Analysis of Rod Pumping Installations,” SPE 9980 presented at the 1982 SPE International Petroleum Exhibition and Technical Symposium, Beijing, March 18-26.
5. Gibbs, S. G.: “Design and Diagnosis of Deviated Rod-Pumped Wells”, SPE Annual Technical Conference and Exhibition, Oct 6-9, 1991, Dallas, USA.
6. Gibbs, S.G.:” Method of Determining Sucker-Rod Pump Performance,” U.S. Patent No. 3,343,409 (Sept. 26, 1967).
7. Knapp, R. M.: “A Dynamic Investigation of Sucker-Rod Pumping,” MS thesis, U. of Kansas, Topeka (Jan. 1969).
8. Lukasiewicz, S. A.: “Dynamic Behavior of the Sucker Rod String in the Inclined Well”, Production Operations Symposium, April 7-9, 1991, Oklahoma City, Oklahoma, USA.
9. Pons, V., “Vertical vs. Deviated wells: Balance of Forces and Equations”, 2021 SouthWestern Petroleum Short Course, Lubbock TX.
10. Pons, V., Gomes, J., “Automatic Iteration on Viscous Damping for Optimal SRP Well Control”, 2024 SouthWestern Petroleum Short Course, Lubbock, TX.
11. Pons-Ehimeakhe, V, “Modified Everitt-Jennings Algorithm, with Dual Iteration on the damping Factors”, SouthWestern Petroleum Short Course, April 2012, Lubbock TX.
12. Pons-Ehimeakhe, V*, Implementing Coulombs Friction for the Calculation of Downhole Cards in Deviated Wells*, SouthWestern Petroleum Short Course, 18-19 April 2012, Lubbock, Texas, USA.
13. Schafer, D. J. and Jennings, J. W.: “An Investigation of Analytical and Numerical Sucker-Rod Pumping Mathematical Models,” paper SPE 16919 presented at the 1987 SPE Annual Technical Conference and Exhibition, Dallas, Sept. 27-30.
14. Snyder, W. E.: “A Method for Computing Down-Hole Forces and Displacements in Oil Wells Pumped With Sucker Rods,” paper 851-37-K presented at the 1963 Spring Meeting of the API Mid-Continent District Div. of Production, Amarillo, March 27-29.
15. Takács, G.: “Sucker-Rod Pumping Manual.” PennWell, 2002.