FLUID LOAD LINE CALCULATION AND FLUID LEVEL CALCULATION: FIELD DATA APPLICATIONS

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ABSTRACT
Ideally when controlling a rod pumped well, it is important to have often and accurate fluid levels. However in the absence of the availability of these measurements, fluid levels must be calculated using fluid properties and pressure gradients. An important part of those calculations is being able to correctly approximate the fluid load. The fluid load is the difference between the upstroke fluid load and the downstroke fluid load. In this paper the accuracy and validity of a methodology for computing fluid load lines and therefore fluid level is verified through the application of the fluid load line calculation to a set of field data, for which a fluid level is available for each stroke analyzed.

1. INTRODUCTION AND MOTIVATIONS:

Most companies today use a software analysis program to compute the downhole data from the surface data, cf. [2, 3, 4]. Downhole data is calculated from surface data using the one dimensional damped wave equation. The damping factor accounts for the losses in energy along the rod string due to viscous friction. It is imperative that the damping be handled properly so that the downhole data output be as accurate as possible.

In the world of reciprocating rod lift, the rate at which the wellbore is depleted of fluids can be greater than the rate at which the reservoir allows the fluids into the wellbore. When not enough fluids are present in the wellbore, a phenomenon called “fluid pound” or “pumped-off” condition happens. When the well is “pumped-off”, there is no or not enough liquid filling the pump to allow the gradual transfer of the fluid load from the traveling valve to the standing valve. “Fluid Pound” results in rod-on-tubing wear, rod slap which can loosen the rod couplings when the rod and tubing come in contact. Increased failures and equipment damage can prove very costly in rod, tubing and system failures, which result in loss of production, see [8].

A common practice is to monitor the amount of fluids in the wellbore and make sure the pump intake pressure and corresponding producing bottom hole pressure are low in comparison with the static reservoir pressure. Monitoring the pump intake pressure may be done in two ways: 1) acquire a fluid level measurement using an acoustic instrument, or 2) approximate the fluid level from the calculated pump loads on the upstroke and downstroke.

Methods describing how to use an acoustic instrument to determine pump intake pressure were first introduced by Walker, see [5, 9, 10]. The best method to determine the fluid level is to acquire the data by using an acoustic instrument. However when fluid level shots are not available, the fluid level can be computed using the upstroke and downstroke loads the pump applies to the rod string. The load the pump applies to the rod string can be calculated from the dynamometer measured surface loads and position during using the one dimensional damped wave equation. The pump fillage can be calculated from the downhole data using a multi-method approach, see [1].

In an effort to correctly estimate the amount of energy lost to viscous forces, an iteration on damping can be performed. In [6], iterations on single and dual damping factors are detailed. A critical quantity in iterating on damping is finding the correct fluid load. Fluid load is the difference between the load on the rod string at the upstroke and the loads on the rod string at the downstroke. Ideally, if pressure measurements are available the upstroke fluid load can be inferred from the pump intake pressure and the downstroke fluid load can be inferred from pump discharge pressure.

The importance of computing the fluid level correctly is two-folds. It is important to know the amount of fluids in the wellbore, so that the pump off/fluid pound condition is avoided. Secondly, it is necessary to be able to accurately estimate the amount of fluids produced to maximize production and minimize downtime.

In the absence of such measurements, fluid load lines can be computed. In [6], a Fluid Load Line Calculcation

(FLLC) method is outlined to determine fluid load lines. This method uses a combination of statistics and first and second derivatives of the downhole position data.

In this paper, field data (including fluid level shots) is analyzed in an effort to show that the fluid load line calculation presented in [6] provides an accurate value for the upstroke fluid load and downstroke fluid load.
In the next section, the fluid load line calculation (FLLC) is outlined. In section 3, background on the field data and the setup of the research presented in this paper is detailed. Results are presented in section 4 and conclusions follow in section 5.

2. DESCRIPTION OF FLUID LOAD LINE COMPUTATION:

Fluid load represents the load of the fluid lifted by the rod string during each stroke. Fluid load is defined as the difference between the load on the upstroke and the load on the downstroke. The pump applies the fluid load to the bottom of the rod string due to the differential pressure acting over the area of the plunger. During the upstroke the differential pressure is equal to the pump discharge pressure (PDP) minus the pump intake pressure (PIP). During the downstroke, the pump does not apply load to the rods because a zero pressure difference is acting over the area of the plunger; and the pump discharge pressure (PDP) is acting above and below the plunger on the downstroke.

If the gas produced in the tubing can be measured, then the pump discharge pressure is somewhat easy to determine. However, in the absence of gas measurements, the upstroke fluid load and the downstroke fluid load have to be observed from the downhole card or inferred mathematically from the downhole data.

As mentioned above, fluid load lines play a critical role in the correct estimation of damping. Traveling and standing valve open and close points play a critical role in the accurate calculation of volumetric pump displacement as well as the accurate calculation of fluid level.

As presented in [6] at the 2012 Southwestern Petroleum Short Course, fluid load lines can be computed using mathematical methods from the downhole data. Two sets of fluid load lines are computed. First, a set of theoretical fluid load lines are computed using the derivatives of the downhole position data.

Ideally, the graphical representation of the upstroke and the downstroke fluid load values should be horizontal lines. If the downhole card is concave, too much damping is used when solving the one-dimensional damped wave equation. Similarly, if the downhole card is convex, too little damping is used when solving the one-dimensional damped wave equation.

In FLLC, two sets of fluid load lines are calculated and compared to serve as a concavity test of sorts. This test compares the statistical distributions of the upstroke points and the downstroke points to the computed values of the fluid load lines. Essentially, the concavity of the upstroke and downstroke fluid load lines is tested.

The fluid load lines are determined by using the first and second derivatives of the position data. The upstroke fluid load line value referred to in this paper as $F0_{up}$ while the downstroke fluid load line value is referred to as $F0_{down}$. The actual fluid load lines $F0_{up}actual$ and $F0_{down}actual$ are computed using the first and second derivatives of the downhole data. The upstroke actual fluid load line $F0_{up}actual$ is calculated as the load corresponding to the top of stroke. The top of stroke is computed by finding the zero of the first derivative of the downhole position data, see [1].

In order to compute the downstroke actual fluid load line $F0_{down}actual$, the location of the transfer point must be calculated. The transfer point is the point at which the load is transferred from the traveling valve to the standing valve. The transfer point is computed using a pump fillage calculation, see [1]. The actual fluid load line $F0_{down}actual$ is taken to be the load of the absolute minimum of the second derivative of the downhole position data after the transfer point, i.e. the lower right corner of the downhole card.

The upstroke and downstroke data is statistically ordered by load in order to produce a probability density function. The maximums of the probability density functions yield a set of load ranges in which most of the upstroke and downstroke data reside. The maximum of the probability density function for the upstroke data is referred to as the calculated fluid load line $F0_{up}calc$ while the maximum of the probability density function for the downstroke data is referred to as the calculated fluid load line $F0_{down}calc$.

In the next section, the setup for the research presented in this paper is detailed.

3. APPLICATION OF ALGORITHM:

In order to validate the FLLC and demonstrate that the values for the fluid load lines calculated through FLLC are accurate and reliable, testing using field data is essential since fluid load lines cannot be directly measured downhole. To this effect, a quantity that relies on fluid load for computation and that can be easily measured would be key to this demonstration.

In [7], Rowlan et. al. presented a comparative analysis of three methods for estimating fluid levels. Fluid level according to Rowlan et. al. can be determined acoustically or estimated from valve tests or from the downhole dynamometer pump card data. In [7], Rowlan et. al. compares the value of pump intake pressure computed from all three methods when applied to a field data set of 16 wells.

According to [7], the Pump Intake Pressure (PIP) can be calculated from the Fluid load (F0) using the following equation:

$$PIP = P_{tub} + 0.433 * \gamma_t * D_p - \frac{\left(F0_{up} - F0_{down}\right)}{A_p}, \qquad (1)$$

Where P_{tub} is the tubing pressure,

γ_t is the fluid specific gravity,
D_p is the true vertical depth,
$F0_{up}$ is the upstroke load,
$F0_{down}$ is the downstroke load,
A_p is the area of the plunger.

Therefore, it is possible to validate the results from the FLLC by verifying that the calculated values for the upstroke and downstroke fluid loads, when inserted into (1), yield a pump intake pressure value close enough to the pump intake pressure inferred from the fluid level shots.

A subset of the field data used in [7] is analyzed using the modified Everitt-Jennings method. The FLLC is then applied to the resulting downhole data to produce the fluid load $F0$. For a subset of 9 wells, pump intake pressure (PIP) values are calculated from (1) using the resulting values of $F0$.
The PIP values calculated with (1) are compared to the PIP values inferred from the fluid level shots as listed in [7].

In the next section, the results from the research are presented.

4. RESULTS:

For the results in this paper, a subset of the field data used in [7] is used. This subset consists of 9 wells, each of which displays a different downhole operating condition.

For each well, fluid level data is recorded along with surface dynamometer load and position data. A set of downhole data is calculated using the modified Everitt-Jennings method with iteration on damping. As part of the iteration on damping, the fluid load lines for a given well are computed using the fluid load lines calculation (FLLC).

From the values of the fluid load lines, pump intake pressure (PIP) is computed from (1). The values are compared to the PIP values inferred from the fluid level shots, as presented in [7].
Without loss of generality, in the following the PIP calculated from the downhole data fluid loads is referred to as calculated PIP, while the PIP from the fluid level shots is referred to as measured PIP.

In table 1, results for the subset of nine wells are presented. The damping factor, the values for the upstroke and downstroke fluid loads are given. Lastly, in the last two columns, the values for the pump intake pressure calculated from the fluid load and the pump intake pressure inferred from the fluid level shots are displayed.

For example 1, a well with a tubing anchor installed but not set properly is studied. The damping factor used when solving the one dimensional damped wave equation, is 0.98. The PIP calculated from (1) reads 317, while the PIP inferred with the fluid level shot is 393.
For example 2, a well anchored with rod stretch is studied. The damping factor is 0.62. The calculated PIP is 139 while the measured PIP is 130.
For example 3, a well with a bad pumping unit tail bearing is studied. The damping factor is 0.92. The calculated PIP is 552 while the measured PIP is 581.
For example 4, a well with fluid pound and unanchored tubing is studied. The damping factor is 0.94. The calculated PIP is 12 while the measured PIP is 45.
For example 5, a well with gas interference is studied. The damping factor is 0.5. The calculated PIP is 747 while the measured PIP is 722.
For example 6, a well with PFL DHM Casing Weight Change is studied. The damping factor is 0.35. The calculated PIP is 292 while the measured PIP is 287.
For example 7, a tagging, unanchored well is studied. The damping factor is 0.92. The calculated PIP is 64 while the measured PIP is 63.9.
For example 8, a well with unaccounted friction is studied. The damping factor is 0.98. The calculated PIP is 326 while the measured PIP is 341.
For example 9, a normal pumped off well is studied. The damping factor is 0.4. The calculated PIP is 61 while the measured PIP is 62.3.

In Figure 1, a scatter plot of the absolute value of the difference between the computed PIP determined using the FLLC and measured PIP determined using fluid level shots is displayed. Over 77% of the wells yield calculated PIP values within 30 psi of the measured PIP. Also, over 44% of the wells yield calculated PIP values within 10 psi of the measured PIP.
In Figures 2-7, downhole cards are displayed. The calculated fluid load lines, resulting from the FLLC, are displayed as black horizontal lines.

In the next section, conclusions are presented.

5. CONCLUSIONS AND DISCUSSION:

The fluid load line calculation (FLLC) provides a robust and accurate way of computing fluid load lines.
As seen from the results in this paper, the fluid load lines computed through FLLC are reasonably accurate since their use in the calculation of pump intake pressure yields values for calculated PIP that match closely the PIP values inferred from fluid level shots.
This paper validates that FLLC can be used efficiently to compute fluid load lines. The use of FLLC greatly improves the ability to adjust damping and also the calculation of pump intake pressure and fluid level in the absence of fluid level shots and gas measurements.

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ACKNOWLEDGEMENTS

6. Special thanks to Lynn Rowlan and Ken Skinner for their help with this paper.

Table 1
Pump Intake Pressure Results for Example 1-9.

Well name	Damping Factor	Upstroke Fluid Load	Downstroke Fluid Load	Fluid Load	Calculated PIP	Measured PIP	ΔPIP
1) Anchored but not set	0.98	5024	895	4129	317	393	76
2) Anchored with Rod Stretch	0.62	7248	1195	6053	139	130	9
3) Bad Tail Bearing	0.92	4915	676	4239	552	581	29
4) Fluid Pound Unanchored Tubing	0.94	2963	257	2706	12	45	33
5) Gas Interference	0.5	5181	417	4764	747	722	25
6) PFL DHM Casing Weight Change	0.35	8029	103	7926	292	287	5
7) Tagging Unanchored	0.92	1902	411	1491	64	63.9	0.1
8) Unaccounted Wellbore Friction	0.98	3540	17	3523	326	341	15
9) V11 Normal Pumped Off Well	0.4	4337	318	4019	61	62.3	1.3

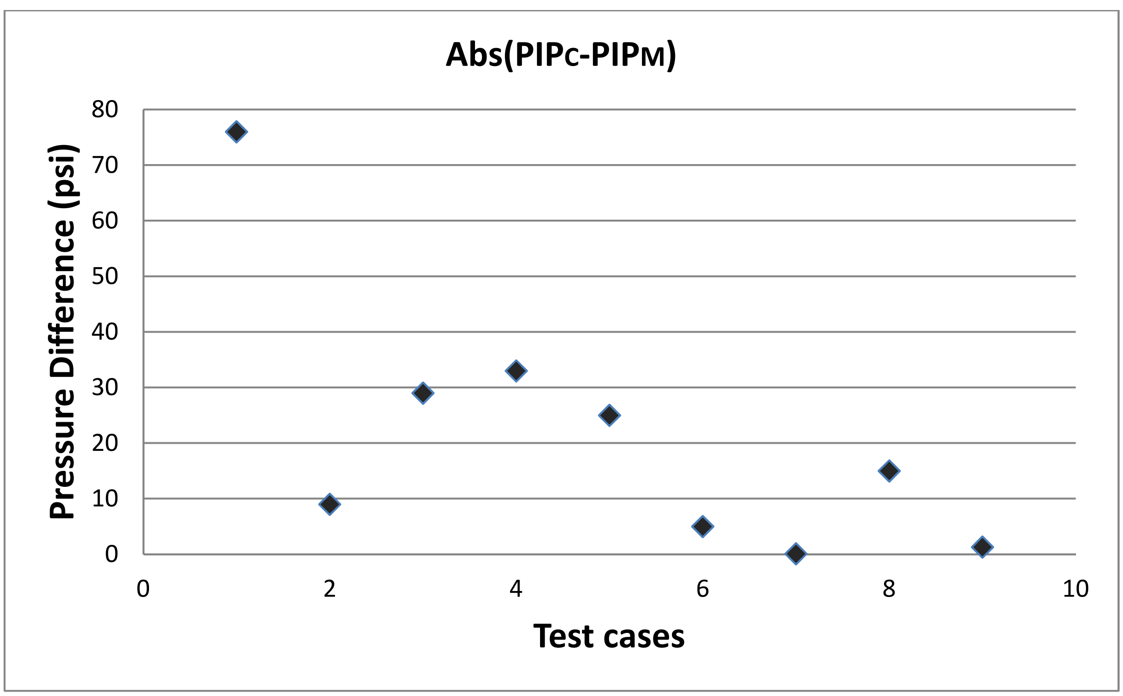

Figure 1 - Absolute value of the difference between calculated PIP from downhole data and measured PIP from fluid level shots.

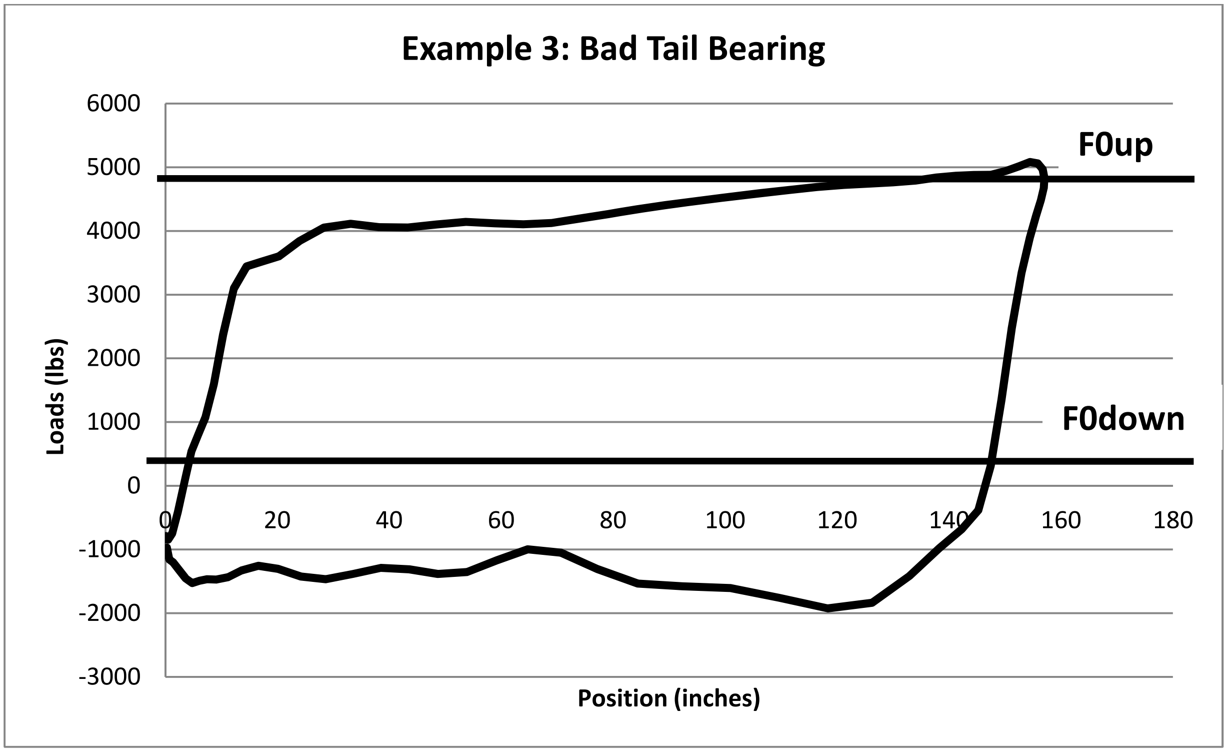

Figure 2 - Fluid load lines Example 3.

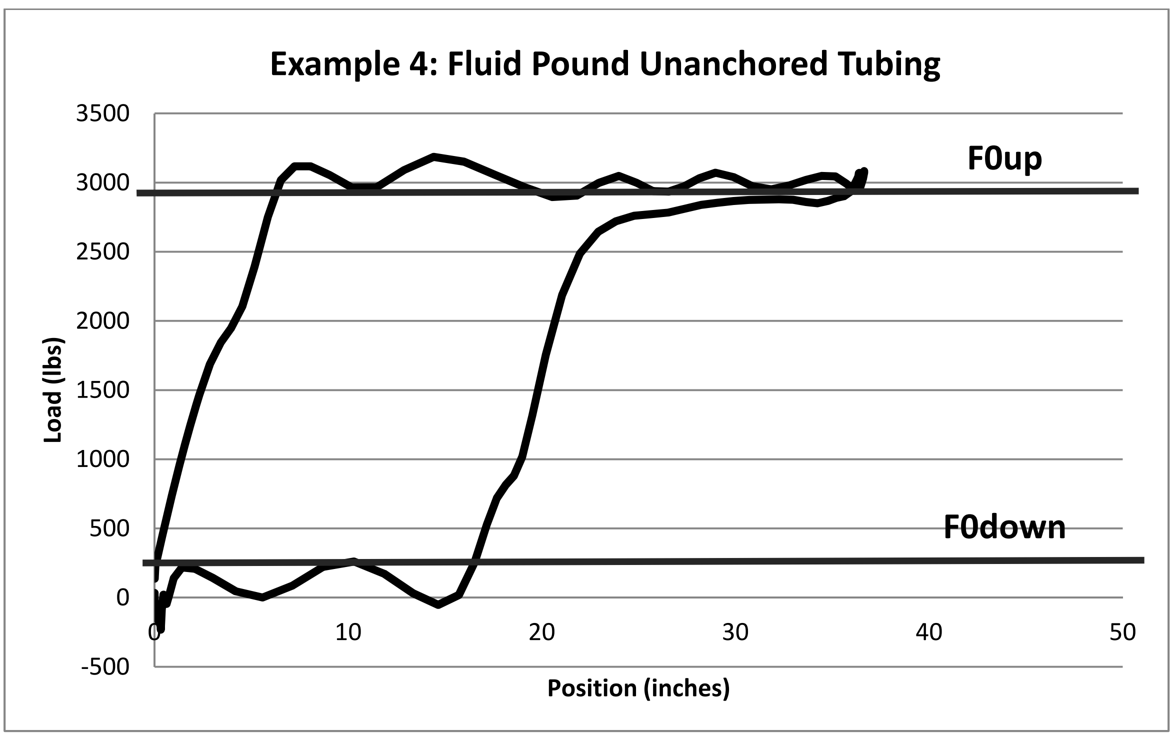

Figure 3 - Fluid load lines Example 4.

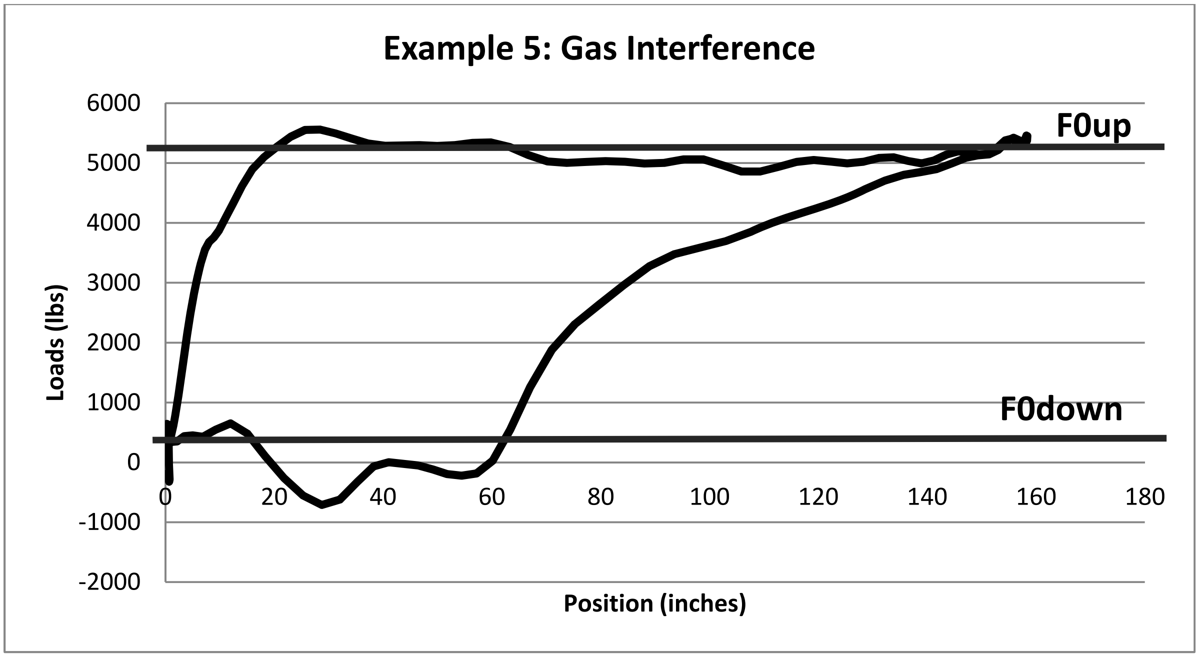

Figure 4 - Fluid load lines Example 5.

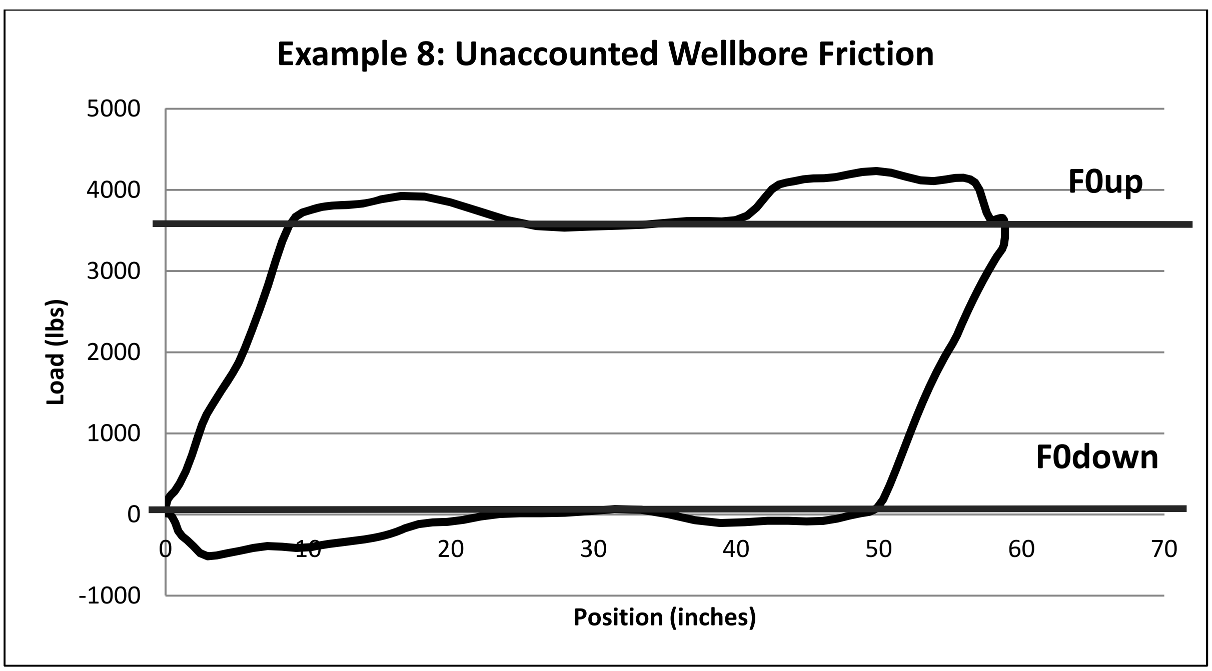

Figure 5 - Fluid load lines Example 8.

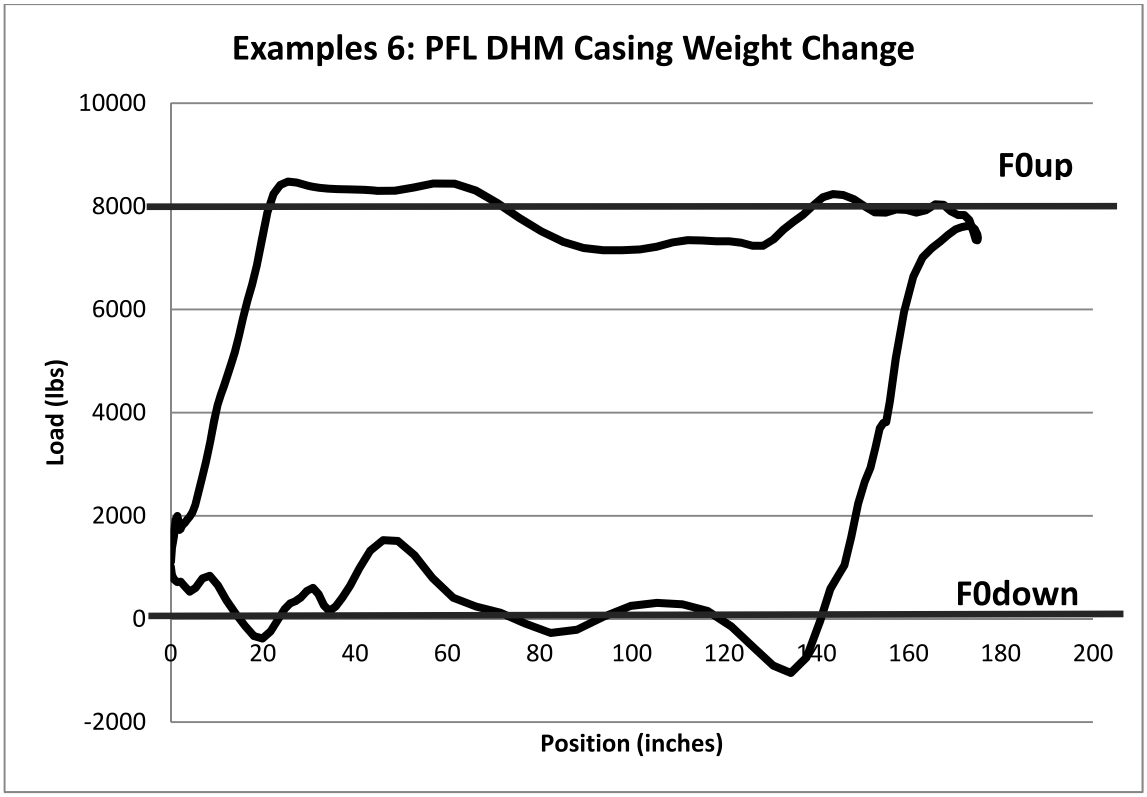

Figure 6 - Fluid load lines Example 6.

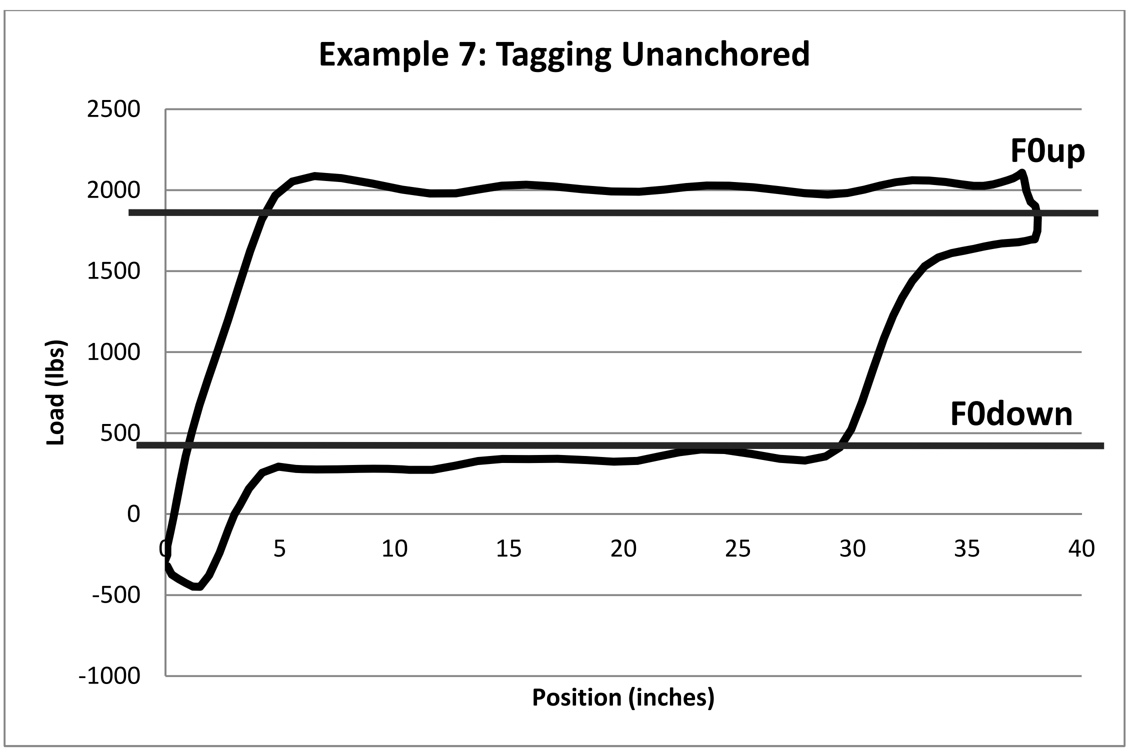

Figure -: Fluid load lines Example 7.