Advances in Dynamometer Technology

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Abstract
Dynamometer testing of sucker rod lifted wells is performed routinely in a safe and efficient manner throughout the world. Advances in dynamometer and computer technology have led to more accurate measurement of force and position at the surface and calculation of loads along the rod string and at the pump. Using an accelerometer to accurately detect sudden small movements of the polished rod gives a detailed picture of the changing load conditions throughout the pumping cycle. Improvement of the polished rod transducer calibration technique has resulted in acquiring dynamometer load measurements equal to the accuracy of precision strain gage load cells. This paper describes advances in dynamometer technology that allow the operator to better monitor and analyze a sucker rod lift system.

Introduction
Recording load and position data on sucker rod lifted wells with a dynamometer transducer has been performed in the oil field for years. In the 1950's the popular Johnson-Fagg dynamometer determined the polished rod load by compressing calibrated steel rings mounted on each side of the polished rod. The surface load and position is scribed onto a rectangular wax coated card as the dynamometer moved with the polished rod. Two disadvantages of the Johnson-Fagg dynamometer were 1) the recorded position was distorted[1] and 2) the installation of this dynamometer between the polished rod clamp and carrier bar was difficult and time consuming. A big advantage the Leutert dynamometer holds over the Johnson-Fagg dynamometer is that it is quickly and easily mounted on the well between the carrier bar and polished rod clamp by using a permanently mounted spool and two specially shaped spacers. The integral hydraulic pump inside the Leutert dynamometer extends two pistons that support the load causing the hydraulic pressure in the Leutert body to change as the well load is applied to the dynamometer. The calibrated springs in the registration unit convert the hydraulic pressure into load. A string attached to the wellhead turns the registration unit in proportion to the polished rod position, thereby scribing the load and position onto the wax dynamometer card for each stroke. The calibrated springs weaken due to use and over time the spring constant gradually changes affecting the accuracy of the loads. Inaccurate load measurement of up to 40% is a documented problem when using the Leutert, which the inaccuracies are caused primarily by the mechanics of the load registration unit[2] and load hysteresis due to drag of the pistons' seals against the cylinder walls. Another disadvantage for both of these wax dynamometer card systems is that the load and position traces have to be tediously digitized by hand, before any detailed analysis can be performed.

Current portable dynamometer technology uses high performance digital data acquisition systems to record dynamometer data for analysis of the sucker rod lift pumping system. The data acquisition system consists of a laptop computer, an analog to digital converter, and a load cell with accelerometer. The load cell uses a strain gauge circuit to accurately measure the load on the polished rod. The load cell can be of the horseshoe type, which is temporarily positioned on the polished rod between the carrier bar and the polished rod clamp, or the donut type, which is permanently mounted. Alternately, a polished rod transducer of a special design that is easily clamped directly onto the polished rod is used to measure load indirectly by sensing the polished rod deformation. The signals from the load cell and accelerometer are connected to the (A/D) converter for conditioning and digitizing at a user-specified sampling frequency. The digital data is then routed to the computer where the signals can be processed, displayed, monitored and recorded. Numerical integration of the acceleration signal is used to calculate the velocity and the position of the polished rod versus time. This polished rod load and position data is typically processed to plot a surface dynamometer card and calculate a pump dynamometer card.

The surface and pump dynamometer plots are used commonly to analyze the operation of a sucker rod pumping system. The surface dynamometer card is the plot of measured polished rod load at the various positions throughout a complete stroke. The pump dynamometer card is a plot of the calculated load at various positions of pump-plunger stroke and represents the load the pump-plunger applies to the bottom of the rod string. Identifying how the pump is performing and analyzing downhole problems is one of the primary uses of the pump dynamometer plot.

Surface dynamometer cards sometimes do not allow complete performance diagnostics of the sucker rod lift system. Measured surface dynamometer cards are valuable for diagnosing rod, structural, and torque loads on the unit and prime mover. When attempting to diagnose downhole pump problems, a visual inspection of the surface dynamometer card is often not sufficient to determine what conditions exist at the pump. Some diagnostics can be done through practical experiences where certain downhole problems are associated with certain surface dynamometer card shapes. In shallow to medium depth wells, interpretation of the surface dynamometer card may be reasonably effective in diagnosing pump performance. In deeper wells, however, the complex dynamics of the lift system usually prevents diagnosing pump performance from surface dynamometer cards.

W.E. Gilbert of Shell developed a mechanically operated downhole dynamometer and he became one of the early pioneers in pump dynamometer card interpretation. The downhole dynamometer provided both an accurate representation of pump-plunger loading and a valuable insight into pump mechanics. In 1936 Gilbert published a classic paper on the interpretation of actual pump dynamometer cards[3]. Glen Albert[4] developed an electronic downhole dynamometer that is used to acquire rod loading and position over a pre-programmed time interval. Both of these downhole dynamometers could be installed at a particular location in the rod string and the dynamometer data was recorded while the well was operating but could only be retrieved by pulling the rods.

During the 1960s, S.G. Gibbs determined it was mathematically feasible to "wave down" the conditions acquired from a surface dynamometer and calculate a precise and reliable downhole dynamometer card.(need reference here) The ability to use a computer[5] to calculate the downhole card has become the basis of modern pump card diagnostic analysis

Polished Rod Position from Accelerometer

Using an accelerometer to accurately detect sudden small movements of the polished rod results in a detailed picture of the polished rod motion throughout a pumping cycle. The accelerometer is a solid-state device and does not require routine maintenance, as does the string type potentiometer. The (A/D) converter continuously acquires "real-time" acceleration data at user selectable time intervals of 15, 30, 60, 120, 240, 480, or greater samples per second. Polished rod velocity, **Fig. 1**, (inches per second) is the integral of acceleration with respect to time, and polished rod stroke length, **Fig. 2**, (inches) is the integral of velocity with respect to time. Accurate polished rod position and velocity data can be determined that describes the motion during a pumping cycle. Velocity of the polished rod in an upward direction is considered positive (+), while velocity in a downward direction is considered negative (-). The time axis of **Fig. 1** and **Fig. 2** is shown in seconds and represents the elapsed time during one stroke. For a small duration of time, there are two points at which the polished rod comes to a stop: 1) the beginning of the upstroke at zero time (or the end of the downstroke), 2) the top of the upstroke (or beginning of the downstroke). The resolution of the polished rod position determined using the accelerometer is dependent on the sampling rate and can be almost continuous, while in comparison the position determined by using string box potentiometers attached to the carrier bar or by inclinometers attached to the walking beam tends to have poor resolution at the areas in the stroke where the polished rod comes to a temporary stop. **Fig. 3** shows actual acquired polished rod position at the beginning of the stroke from a beam mounted inclinometer, the red curve is the smoothing of the data required to prevent false load spikes from appearing on the pump dynamometer card when the position data is processed using the wave equation.

Sudden changes in the speed of the pumping system is sometimes caused by abnormal load changes being applied to the rod string, pumping unit, and or prime mover and are clearly reflected in the acceleration signal. When observing the acceleration data in real time the operator will often hear a sound at the time when these abnormal load changes occur and he can relate the sound he hears to certain spikes in the acceleration data. These noises are reflected in the acceleration versus time display and can be used by the operator to detect a potential problem and identify its source in relation to the stroke. A fluid pound is a sudden change in load on the rods and is an example of a downhole event that frequently is seen as an acceleration spike at the polished rod.

Polished Rod and Plunger Position

The polished rod position and plunger position versus time plots aid in the understanding of the movement of the pump plunger relative to the polished rod position. Rods stretch when they pick up the differential fluid load on the plunger during the upstroke. Rods shorten when releasing or transferring the fluid load from the rods back to the tubing during the beginning of the down stroke. Unanchored tubing stretches during the transfer of fluid load from the rods to the tubing during the early part of the down stroke and shortens when the fluid load is transferred from the tubing to the rods.

For one complete stroke the positions of both the polished rod and the pump plunger are shown by the two curves in **Fig. 4**. This figure is an excellent example of the effect of rod stretch on plunger motion for a well with anchored tubing. During the 8.37 seconds duration of one stroke, the polished rod position curve has a near-sinusoidal shape with a maximum amplitude, S, of 168 inches, while the magnitude of the plunger stroke, Sp, is 153.6 inches. Starting at the beginning of the upstroke, point A, the polished rod moves upward but the pump plunger remains stationary while the rods gradually stretch, until the fluid load, force from the differential pressure across the plunger, is transferred from the tubing (standing valve) to the stretched rods (traveling valve). At point B, the rods have stretched enough to balance the fluid load on the plunger and the plunger begins to move upward. The plunger does not move relative to the anchored tubing for the time period from point A to point B and the plunger has near-zero velocity shown in **Fig. 5** during this time period. During the rest of the upstroke, the rod stretch remains approximately constant and the plunger and polished rod move in sync. Point C is at the beginning of the polished rod down stroke, the plunger again remains stationary while the rod stretch decreases. The fluid load at point C is beginning to be transferred from the rods and plunger back to the closed standing valve supported by the anchored tubing. At point D, where the stretch of the rods becomes zero, the plunger is completely unloaded and again both plunger and polished rod move together during the down stroke. This process is repeated for each additional stroke. A horizontal line for plunger position from points A to B and from points C to D is an indication that the traveling and standing valve are not leaking, the tubing anchor is holding, and very little fluid slippage through the clearance between the plunger and barrel is occurring.

Example Pump Card

Fig. 6 is the example pump card that corresponds to **Fig. 4** and **Fig. 5**. The maximum plunger travel, MPT, is the maximum length of the plunger movement with respect to the pump barrel during one complete stroke. The fluid load, Fo, is the force caused by differential pressure acting on the pump plunger and acts on the traveling valve on the upstroke and is transferred to the standing valve on the down stroke. The differential pressure is the difference between the pressure due to the tubing fluids and the pressure in the pump barrel. The pressure in the pump barrel during the upstroke is related to the pressure at the pump intake minus the pressure drop through the standing valve. The pressure at the pump intake is equal to the annulus pressure at the depth of the standing valve minus the pressure drop through the dip tube, gas anchor (if present) or screen that may be attached below the pump. In most cases the pressure drop through the assemblies attached to the pump are considered to be small and are ignored. When fluid entry into the pump in partially blocked, a long dip tube is attached to the pump intake, or the viscosity of the fluid is high; then this pressure drop should not be ignored, because the additional pressure affects the fluid load that is applied to the pump. The magnitude of the fluid load is equal to the pump discharge pressure minus the pump intake pressure multiplied by the plunger area. From points B to C the rods carry the fluid load, when the traveling valve is closed. From points D to A the tubing carries the fluid load, when the standing valve is closed. The effective plunger travel, EPT, is the length of the plunger travel when the full fluid load is acting on the standing valve.

The successive steps in the pump operation are:

1. At the start of the upstroke (point A), the traveling valve and standing valve are both closed.
2. From point A to point B, the fluid load is fully carried by the tubing prior to point A and is gradually transferred to the rods at point B. The load transfers as the rods stretch to pick up the fluid load (Fo). If the tubing is anchored, the plunger does not move relative

to the tubing. The pressure in the pump barrel (Pb)decreases from the static tubing pressure (Pt) to the pump intake pressure (Pint) and any free gas in the space between valves expands..

3. The standing valve begins to open at B, allowing fluid to enter the pump when the pressure in the pump drops below the pump intake pressure (Pint).
4. From point B to C, the rods carry the fluid load while well fluids are drawn into the pump.
5. At C, the standing valve closes as the plunger starts down, and the traveling valve remains closed until the pressure inside the pump is slightly greater than the pump discharge pressure (Pd) that is equal to the static tubing pressure (Pt).
6. From C to D, gas in the pump (if present) is compressed as the plunger moves down to increase pressure on the fluid from the intake pressure (Pint) to the static pressure in the tubing. As the fluid in the pump barrel is compressed, then the fluid load is gradually transferred from the rods to the tubing. The plunger does not move, if the pump barrel is full of an incompressible fluid, until the rod stretch is recovered.
7. At D, the pump barrel pressure (Pb) equals the static tubing pressure (Pt), and the traveling valve opens.
8. From D to A, the fluid in the pump is displaced through the traveling valve into the tubing as the closed standing valve holds the fluid load on the tubing.

During the upstroke the fluid load, FoUp, applied to the rod string is due to differential pressure acting on the plunger and is equal to the pump discharge pressure minus the pump intake pressure time the area of the pump plunger. For low viscosity fluids the friction force between barrel and plunger is usually small and the pressure drop across the standing valve is usually small so that the barrel pressure is close to the pump intake pressure. On the downstroke the fluid load the pump applies to the rods is near zero, because the pressure inside the pump barrel is usually almost equal to the pump discharge pressure. The friction force between barrel and plunger and the force due to fluids moving through traveling valve are usually small. For viscous fluids the friction and pressure drop through the valve may become significant. In addition to FoMax, it is useful to show two additional reference lines on the pump card as shown in **Fig. 7**:

1) On the downstroke, FoDn represents the average pump card loads. Generally this line should be near zero load.
2) On the upstroke, FoUp represents the average pump card loads. When the well is produced at is maximum potential with low pump intake pressure, then the fluid load on the upstroke should be near the reference line of FoMax.

FoMax is equal to the pump discharge pressure times the plunger area, this is the maximum fluid load required to lift the fluid to the surface, with pump intake pressure near zero and the well providing no help in lifting the fluid to the surface.

Polished Rod Transducer

The polished rod transducer, PRT, is a very popular and versatile dynamometer that can be quickly installed in less than 30 seconds simply by clamping it to the polished rod below the carrier bar. The PRT is used to gather load and position data that allows the calculation and determination of a surface dynamometer card, a pump card and traveling and standing valve tests when using the portable Well Analyzer and Total Well Management[6] software. The dynamometer data is sufficiently accurate for most pumping unit analysis in a very safe manner with a minimum of effort.

The position of the plunger in the pump barrel is not changed by the installation of the PRT, as occurs in some horseshoe dynamometer installations. For this reason, the polished rod transducer analysis may be more representative of actual well performance than an analysis using a horseshoe transducer that raises the rods and plunger in the pump. The PRT[7] contains load measuring semi-conductor strain gauges and an accurate accelerometer. It measures the change in diameter of the polished rod and converts the change in diameter to the change in load on the polished rod. The extremely small diameter changes of the polished rod are detected using sensitive solid-state strain gauges. The strain in the radial direction resulting from a stress in the axial direction is converted into changes in axial load on the polished rod using a generalized form of Hooke's law, $\varepsilon_z = \sigma_z / E$, for homogeneous isotropic materials and $\varepsilon_r = \mu\varepsilon_z$. Since the Poisson's ratio (μ) for steel is about 0.3, the radial strain (ε_r) is about 30% of the axial strain (ε_z). The PRT is approximately 3 times more sensitive than the normal strain gauge load cell that measures axial strain. The acceleration data is twice integrated as discussed in a previous section to determine the polished rod position. The change in load for a pump stroke and the calculated positions from the acceleration data are used to generate a surface dynamometer card. The software calculates a pump card using the wave equation solution for rod loads and displacements, the acquired relative load values and the polished rod position data. The relative loads of the surface and downhole cards are calibrated by software using the principle that the average mechanical load the pump applies to the rod string on the downstroke when the traveling valve is open should equal zero and thus the pump card should rest on the zero load line. The surface card, which contains both positive and negative relative load values is adjusted, by the same offset that is utilized to set the average of the down stroke pump card loads to zero, resulting in the display of absolute load values. Software performs these calculations and plots the calibrated surface and pump cards.

If the proper amount of friction along the rod string is NOT accounted for by the wave equation (based on average damping factors) when waving down to the resultant pump card then the surface dynamometer card loads may be offset by a value representing an “unaccounted friction”. This unaccounted friction shifts the surface loads upward by approximately 1/2 of the value of the unaccounted friction, because similar amounts of friction usually occur on both the up stroke and the down stroke. Paraffin, a crooked hole, or viscous oils can cause unaccounted friction. Shown in **Fig. 7** is an example of a pump card determined from data acquired using an accurate calibrated load cell; due to unexpected friction from accumulated paraffin along the rod string the pump card has approximately 850 lbs of unaccounted friction on both the up stroke and the down stroke. If the PRT had been used to acquire the dynamometer data on this well, then the surface loads would be shifted upward by 850 pounds. A horseshoe transducer should be used in special cases where the drag or damping factor on the sucker rods cannot be estimated with reasonable accuracy.

Modifications in the software have also improved the accuracy of surface loads determined when using a PRT on wells that are tagging on the down stroke. Acquiring dynamometer data on wells with a tag on the down stroke is often impossible when installing a horseshoe transducer between the pumping unit carrier bar and the permanent polished rod clamp, because the horseshoe load cell lifts the pump up 3 inches, re-spacing the pump, and the tag usually goes away. **Fig. 8** shows how setting the average of the down stroke pump card loads to zero improves accuracy of surface loads on wells with a tag. In the past the minimum pump card load was set on zero, which resulted in an upward shift of the surface loads equal to the absolute value of the negative tag. The calculated peak polished rod load without the proper adjustment for the tag is 23,843 pounds, which is too high by the 2,914 pounds of negative load being applied by the tag. The surface PRT dynamometer card's peak polished rod load is a more accurate 21,041 pounds when the pump card load offset due to tagging is adjusted properly.

Fig. 9 compares the of polished rod and pump dynamometer cards data acquired using simultaneously the PRT and a horseshoe load cell on the same well. The shapes of the dynamometer cards are the same and the downhole pump fillage of 55% was calculated to be the same for both systems. The average deviation is only 50 lbs when comparing the measured loads of the two systems, while absolute maximum deviation is 250 lbs. The peak polished rod load, PPRL, determined using the PRT is within 171 lbs of PPRL of 13,012 lbs determined by using the horseshoe load cell. The minimum polished rod load, MPRL, determined using the PRT is within 60 lbs of the MPRL of 5,885 lbs determined by using the horseshoe load cell. The difference in load acquired using the PRT when compared to the load acquired with a horse load cell is small and the loads are more accurate than would normally be expected when comparing two load cells.

Horseshoe Load Cells

Horseshoe transducers are used to very accurately measures polished rod load using 12 strain gauges, which are mounted on three supporting members. Offloading or side loading due to the carrier bar being tilted does not affect the accuracy of the load measurement due to the averaging effect of the multiple gages. The transducers are manufactured with instrumentation grade stainless steel and incorporate a high accuracy accelerometer from which the software computes the velocity and position of the polished rod. The horseshoe transducer is calibrated to yield an overall accuracy of 0.5% of range or better. The 4" horseshoe transducer is rated at 30,000 Lb. and the 5" horseshoe transducer is rated at 50,000 Lb.

A horseshoe transducer is installed between the pumping unit carrier bar and the permanent polished rod clamp. To install the 4" horseshoe transducer, a temporary polished rod clamp is positioned on the polished rod about 4 inches above the stuffing box when the polished rod is stopped at the bottom of the stroke. A temporary knock-off block is located on the stuffing box as the polished rod with the temporarily installed clamp is on the down stroke. Also when on the down stroke, the motor is turned off the momentum of the system causes the polished rod to continue downward until the temporarily installed polished rod clamp comes in contact with the knock-off assembly. The pumping unit brake is set when the polished rod is at the bottom of the stroke. This causes the permanently installed polished rod clamp that normally rests on the carrier bar to be several inches above the carrier bar. The 4" O.D. transducer is 3" high, and it is positioned into the free space between the carrier bar and the permanent polished rod clamp. The pumping unit brake is then released, causing the load to be transferred from the knock-off block to the carrier bar. Then the knock-off block is removed and the motor is started again.

An alternative system uses a hydraulic lift horseshoe dynamometer that requires permanent installation of an inexpensive spacer spool over the polished rod positioned between the polished rod clamp and the pumping unit carrier bar. This 5” OD horseshoe load cell dynamometer system is designed to facilitate safe and quick installation of the load cell, and to eliminate measurement errors caused by changes in pump spacing resulting from temporary installation of a horseshoe transducer between the carrier bar and the permanent polished rod clamp. When a dynamometer test is desired, the horseshoe transducer and a hydraulic lift assembly are easily inserted into the spool. The hydraulic lift is actuated using a small portable hydraulic pump, which transfers the polished rod load from the spacer onto the 5" horseshoe load cell. After a ¼ inch thick spacer plate is inserted between the hydraulic lift and the horseshoe transducer, the hydraulic liquid is bled back into the pump, and the polished rod load is lowered onto the horseshoe transducer, spacer plate, and the hydraulic jack. The entire polished rod load is supported on the horseshoe transducer. Once the pressure in the pump is released, then the hose and fitting can be disconnected from the hydraulic jack. After the dynamometer test, the horseshoe transducer, hydraulic jack and spacer are removed in reverse manner leaving the spool on the well for future tests when desired.

The main advantage of the 5" horseshoe transducer hydraulic jack assembly is that the polished rod is raised less than 1/4" during installation of the load cell. Thus, the pump plunger continues in the same operating position in the pump when the dynamometer test is performed. Also, the installation of the 5" horseshoe transducer (using the hydraulic jack) is easier and safer than installation of a horseshoe transducer that requires separating the pumping unit carrier bar from the permanent polished rod clamp a sufficient distance (3 inches) so that the horseshoe transducer can be inserted between the carrier bar and the clamp. The disadvantage of the horseshoe transducer hydraulic jack assembly is that a spool must be placed (in general permanently) over the polished rod between the pumping unit carrier bar and the polished rod clamp requiring a spool for each well.

Modified Leutert Dynamometer

With a conventional Leutert system the surface dynamometer load and position data are traced on a waxy paper card. The dynamometer trace on the card is generally not digitized and is used only for qualitative interpretation of pump operation. Modifying the Leutert dynamometer unit to communicate with an A/D device and then processing the dynamometer data with software, allows the operator to perform a very detailed analysis of the total sucker rod lift system. The main concern with using a hydraulic system to measure varying loads is inaccuracy of the acquired load data, caused by hysteresis due to excessive friction in the registration unit and in the cup piston seals. Hysteresis is defined as a lag effect when the forces acting on a body are reversed. When load is applied to the Leutert dynamometer and then released to a specific load, the measured load is higher than the actual load. Hysteresis will result in erroneous load readings, which affect rod stress, gearbox loading and other calculations. The replacement of the registration unit with electronic sensors results in a reduction of a large amount of hystheresis. The registration unit has a small moving piston that reacts to pressure changes within the Leutert. This moving piston is thought to contribute to the majority of the hystheresis effects. There is also a spring and linkages, which transfer the load differences to a stylus, which traces on a wax-coated card attached to a drum. The registration unit not only contributes to the hystheresis, but also requires the highest amount of maintenance. By replacing the registration unit with a pressure transducer and accelerometer, then the load data is more accurate, the acquired load values are repeatable and maintenance problems are reduced. Hystheresis for the modified Leutert is usually reduced to within 0.5 and 1.5% and is almost equal to the precision of a calibrated strain gauge load cell.

Instead of using horseshoe a load cell or PRT for acquiring dynamometer data, some operating companies have decided to modify existing Leutert dynamometers based on the following factors:

1) Current operator experience dictates using the same type of portable system.
2) Leutert dynamometer is easier to install on the polished rod, than the 4" horseshoe type load cell that requires the rods to be "stacked off" on the stuffing box. If stacking off is not performed correctly, this practice can cause damage to the stuffing box and/or polished rod and at times can be dangerous if the pumping unit break is not operating properly.
3) The Leutert dynamometer is used by the operating company, so the wells already have Leutert spacers installed, precluding the associated cost of purchasing the spool and washers for a 5" load cell.
4) The Leutert dynamometer only raises the rods l/16 to l/8 of an inch, resulting in data representative of actual operating conditions.

Permanently Mounted Donut Load Cells

The load cell is cylindrical (donut) shaped and usually has strain gauge rosettes located at equal distances around cylindrical body. The donut load cell is permanently mounted over the polished rod between the carrier bar and the polished rod clamp. Position of the walking beam is often determined through some type transducers where the voltage signal is proportional to the angle swept through by the walking beam. Generally these installations are used in conjunction with pump off controllers or as field end-elements in SCADA systems. The most accurate dynamometer measurements are obtained using a calibrated strain gauge load cell, which directly measures the load on the polished rod.

Proper analysis of dynamometer data depends on accurately measured loads and the polished rod loads should be acquired using a calibrated load cell. Often the load measured with a permanently mounted, donut type load cell can be in error due to:

1) Damage to the load cell,
2) An error in the calibration of the load cell,
3) A load cell that is not centrally loaded at the top and bottom,
4) The load cell's offset for zero load has changed or is unknown and the well loads must be stacked off of the load cell to determine the zero offset, or
5) An error in the calibration of the controller incorrectly converting the mV/V output from the load cell into pounds of load.

In order to verify the accuracy of the measurements and the operation of the pumping system, the permanently mounted donut load cells can be used to measure load data in conjunction with portable dynamometer data acquisition systems. An external string box or position transducer is sometimes used to determine position, but concerns about accuracy of position data still exist as previously discussed. A special accelerometer transducer, similar in size to the PRT but containing only the accelerometer function, can be used to determine position. This special accelerometer transducer is used to replace any string box or inclinometer that could be used with any type of load cell. The special accelerometer transducer can be quickly installed and is simply clamped to the polished rod below the carrier bar. The special accelerometer is small and can be easily installed on a well to obtain acceleration data along with load data from the separate load cell.

Dynamometer Data

The previous sections in this paper describe advances in dynamometer technology, which allow the operator to better monitor and analyze a sucker rod lift system. Acquiring accurate dynamometer data representative of the well's normal operating conditions requires the operator to take care when he acquires data. A sucker rod pump operated in a continuous mode is constantly lifting fluids to the surface, while maintaining steady state conditions with a constant producing bottom hole pressure and continuous inflow into the wellbore. The pumping unit must be stopped in order to attach a dynamometer transducer, for safety purposes the operator should disconnect the power and set the break. The normal steady state operating conditions are disturbed during the time the well is shut down. It is recommended the pumping unit operate for a sufficient time after being shut down until the well again operates at stabilizes conditions, then the acquisition of dynamometer data will be representative of the conditions of how the well normally produced. Other times the problem needing analysis may be of an intermittent nature and the operator must acquire data when the problem occurs, this may sometimes require the operator to collect data for extended periods of time.

Analysis of the collected dynamometer data shows the loads and horsepower requirements of the surface dynamometer card and the pump card. A traveling valve and standing valve test can be performed. A comparison of the measured load to the calculated buoyant rod weight is an excellent check that the well's rod data are entered correctly. The traveling valve and standing valve tests allow the calculation of pump intake pressure, pump leakage, traveling valve and plunger performance and standing valve leakage performance. Gearbox loading is calculated by software using the polished rod load and position data. The counterweight moment must be calculated using the known properties of the cranks, counterweights and counterweight positions or the counterweight moment can be determined by measurement of the counter balance effect using the accurate load transducer. Gearbox loadings and a permissible load diagram are calculated and displayed. Dynamometer data processed with software allows the analysis of polished rod power requirement, pumping unit beam loadings, rod loadings, pump power requirements, and pump performance. These types of analysis allow the operator to effectively monitor and analyze the sucker rod lift system.

Conclusion

Technology derived from computer software and improvements in transducers is continually evolving. New technology is improving the ability of the operator to better understand and analyze the operation of the sucker rod lift equipment. The advent of portable computers and software has made analysis and acquisition of dynamometer data easier, faster, and more accurate. Use of a portable system permits further in-depth analysis of the sucker rod pumping system at the well site. Polished rod position data determined by using an accelerometer is far superior to the position data determined from other devices. Accelerometers can be used to accurately determine position in conjunction with any type of load cell. Polished rod loads determined using a polished rod transducer are usually accurate to with-in the expected 0.5 % error of a calibrated load cell.

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Nomenclature

MPT = Maximum Length of the Plunger Movement
Fo = Fluid Load Acting on the Plunger
EPT = Effective Plunger Travel
Pt = Static Pressure in Tubing above the Pump
Pd = Pump Discharge Pressure
Pint = Pump Intake Pressure
Ap = Plunger Area
FoMax = Maximum Fluid Load on the Plunger
ε = radial strain
μ = Poisson's Ratio
σ = axial stress
E = Young's Modulus
FoUp = Fluid Load on Up Stroke
FoDn = Fluid Load on Down Stroke

Fig. 1 – Polished Rod Velocity is the Integration of Acceleration with Respect to Time.

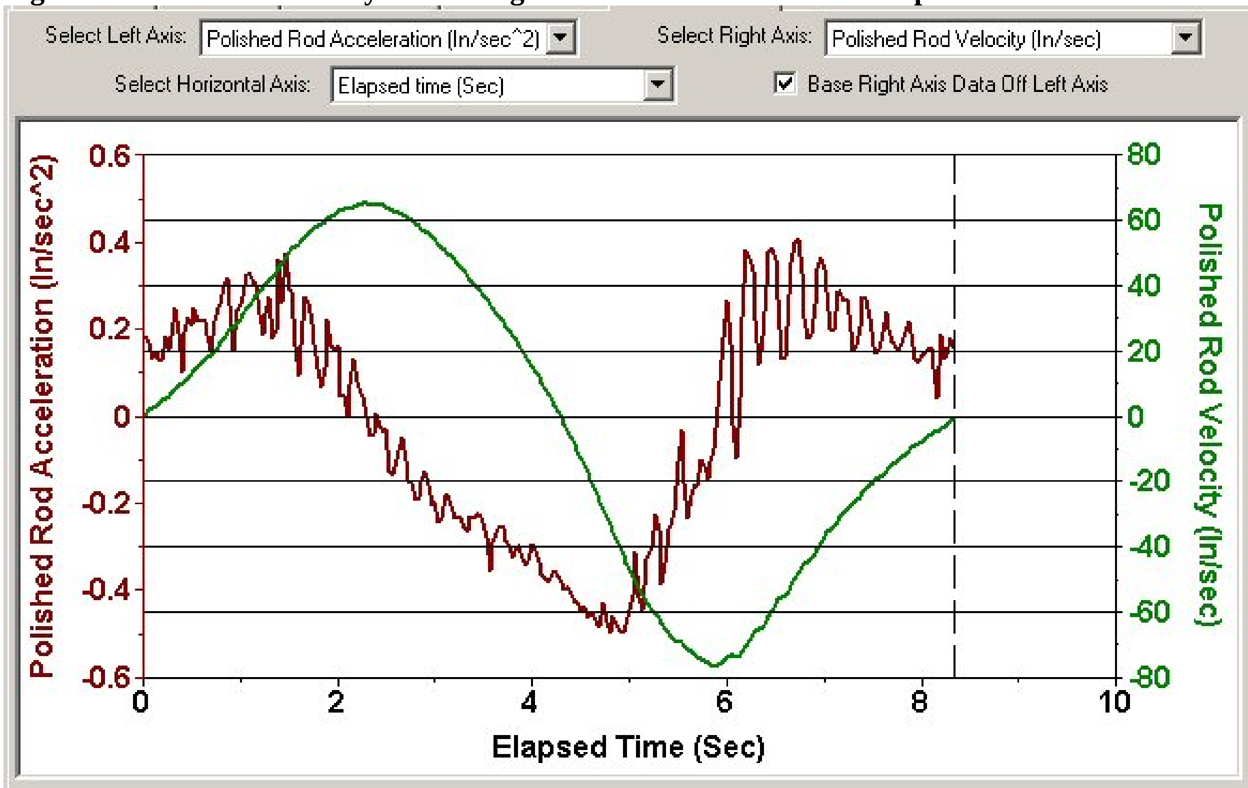

Fig. 2 – Polished Rod Position is the Integration of Velocity with Respect to Time.

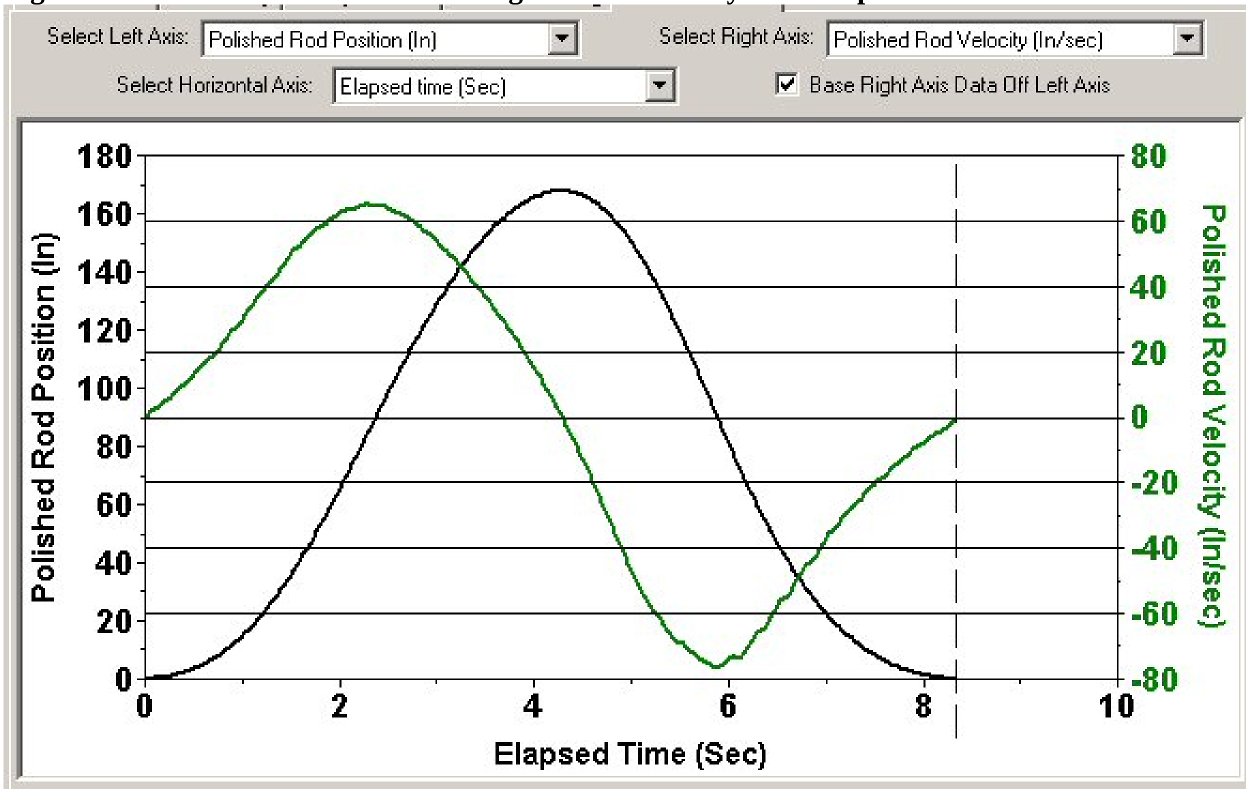

Fig. 3 – Polished Rod Position from Inclinometer Requires Smoothing of Error.

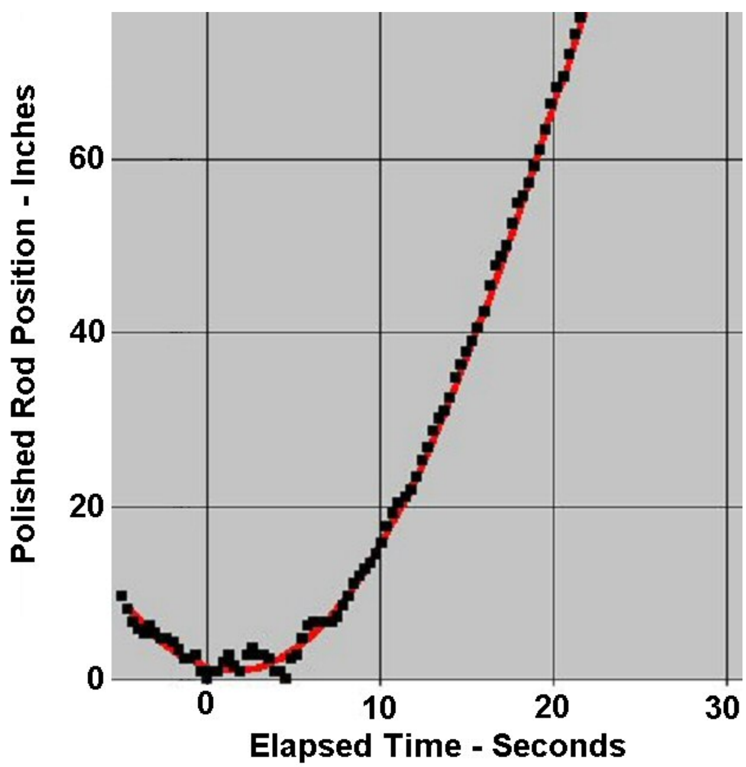

Fig. 4 – Polished Rod and Plunger Position Versus Elapsed Time for Anchored Tubing.

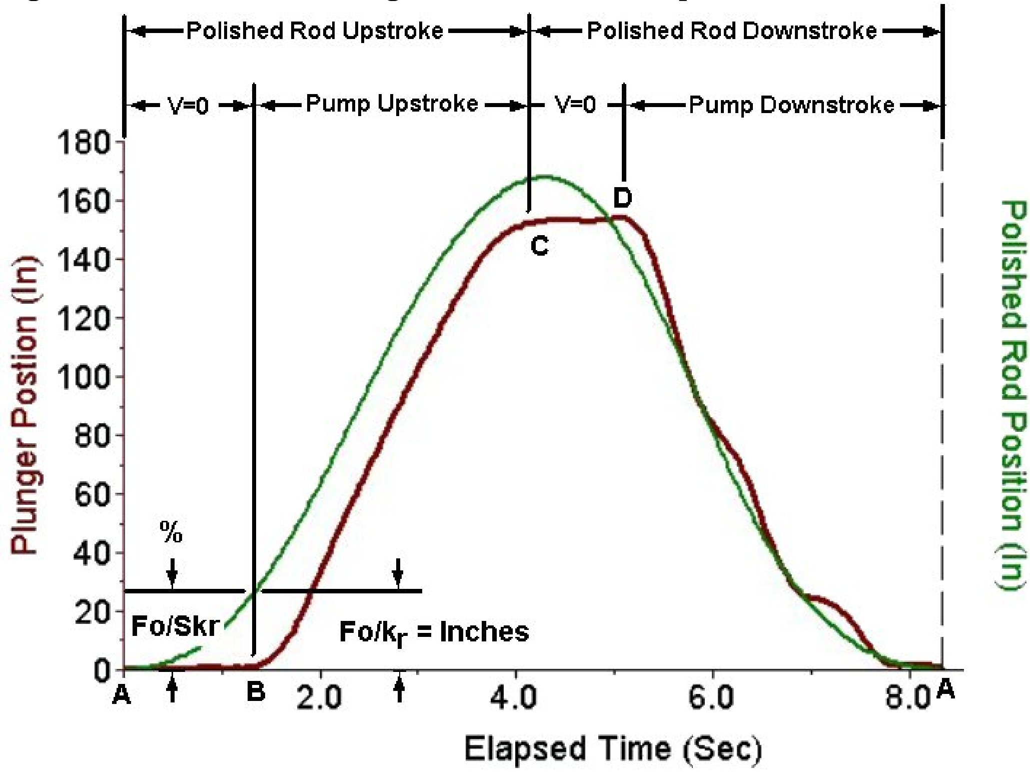

Fig. 5 – Polished Rod and Plunger Velocity Versus Elapsed Time for Anchored Tubing.

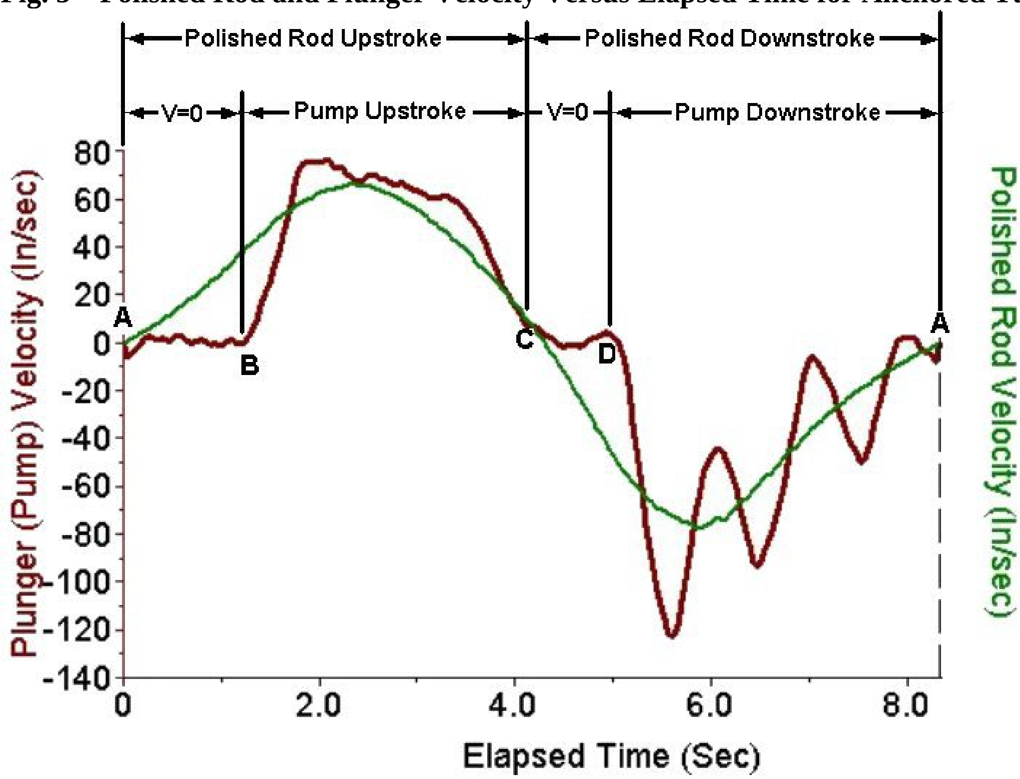

Fig. 6 – Example Pump Card w/ Load (k-lbs) and Position (inches)

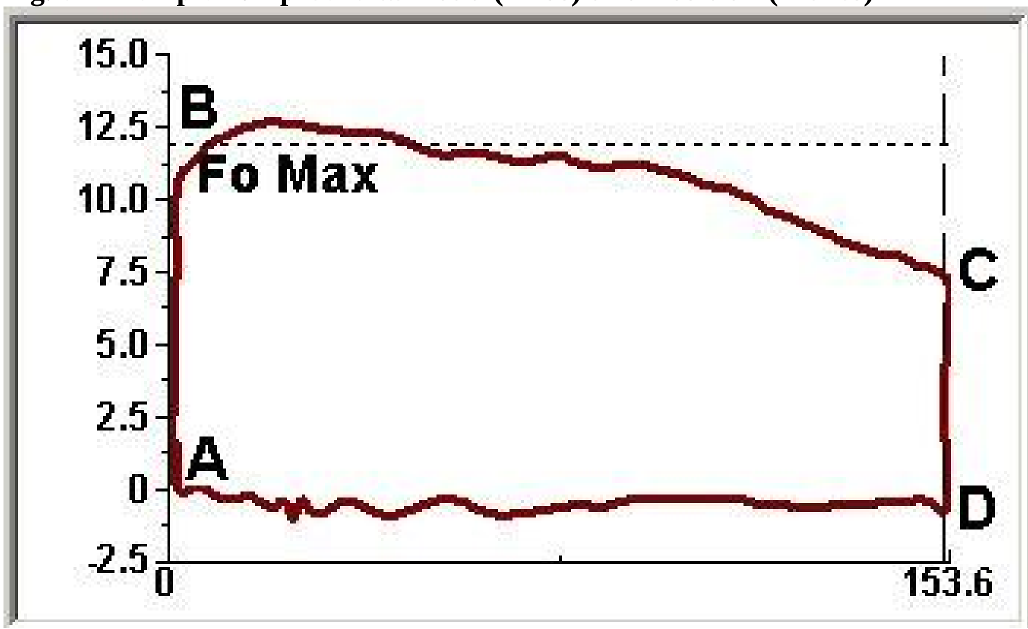

Fig. 7 – Pump Card with Unaccounted Friction from Paraffin

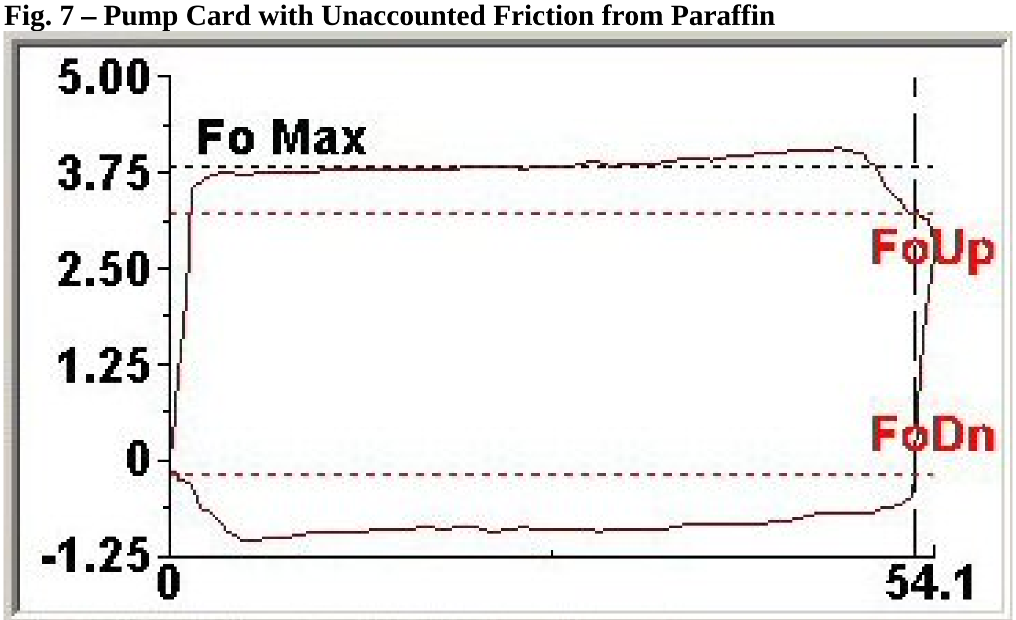

Fig. 8 – Surface PRT Dynamometer Adjusted for Load Offset due to Tagging on the Down Stroke

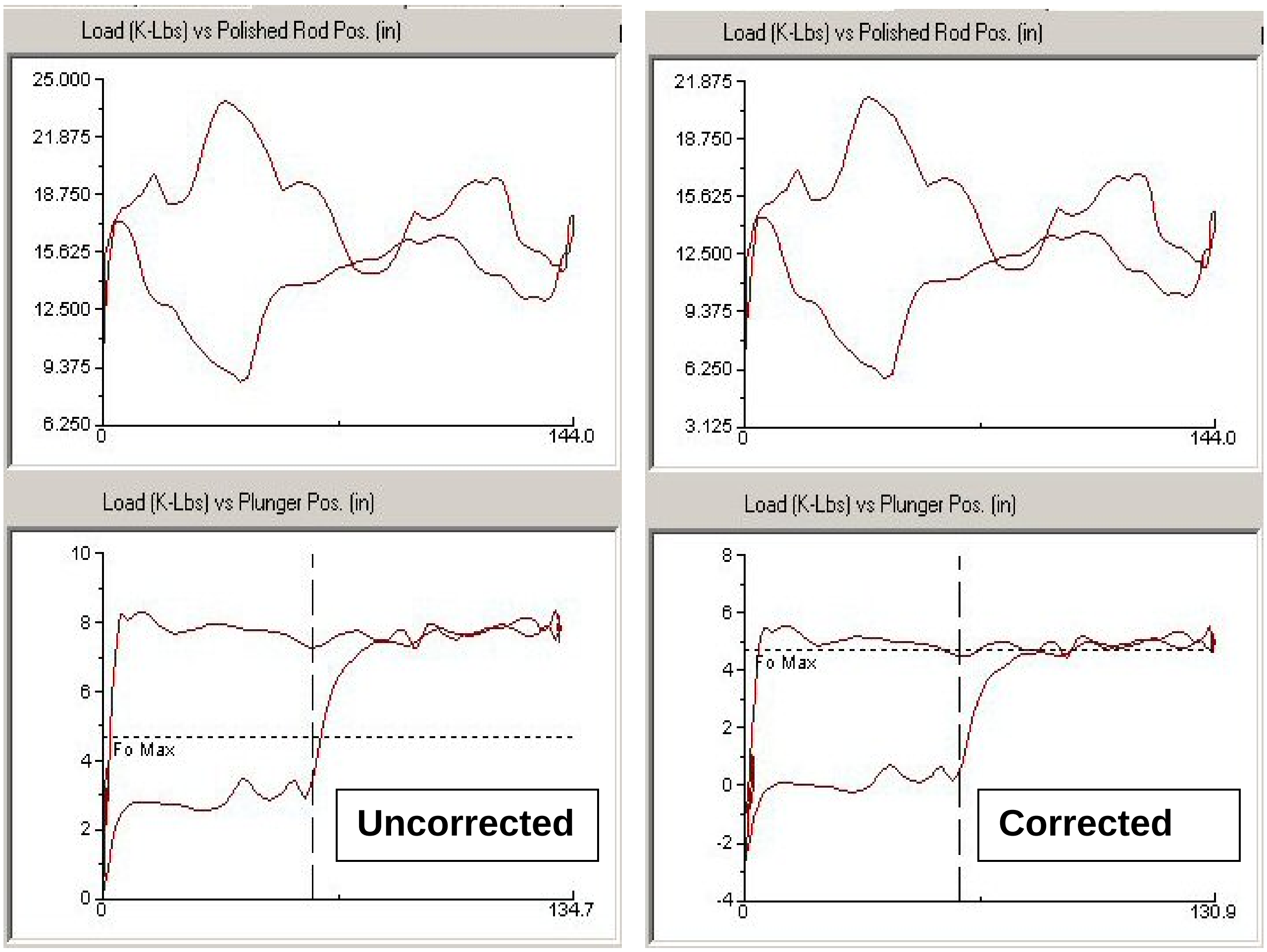

Fig. 9 – Comparison of Polished Rod and Pump Dynamometer Cards for PRT and Load Cells