Accurate Load & Position Measurement Is Critical to Quality Dynamometer Analysis

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Quality Dynamometer Analysis

- Dynamometer Overview
- Load Measurement Methodology
  - Beam-Mounted Strain Gauge
  - Polished Rod Load Cell
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- Position Measurement Methodology
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  - Inclinometer
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DYNAMOMETER OVERVIEW
Today’s dynamometer systems allows for near real-time monitoring and analysis of the performance of rod pump systems.

Rod pump controllers (RPCs), SCADA, and diagnostic software have greatly increased the availability of dynamometer data, but not necessarily the quality of this data.

This is not a new problem, Kemler (1935) described early problems with damping and phase lag of dynamometer data.
What Is a Dynamometer Card?

- Merriam-Webster: “an instrument for measuring mechanical force”
- For reciprocating rod lift applications, it measures the force applied to the rod string throughout the pumping cycle
- The basic measurements required are synchronized polished rod load and polished rod position
Beam-Mounted Strain Gauge

- Measures changes in tension of the walking beam caused by changes in polished rod load
- Does not require polished rod to be clamped off during installation or replacement
- Reduced likelihood of cable damage during normal operation or workover
- Not subjected to shock loading if rods float on the downstroke
- May have integrated position measurement, requiring only one cable for installation
Beam-Mounted Strain Gauge Sources of Error

- No direct relationship between strain gauge output and force applied to the polished rod
  - Each installation must be “calibrated” to expected minimum and maximum polished rod loads
  - RPC must be programmed with the min/max loads from a portable dynamometer or predictive program during installation
- Polished rod load is not the only force that causes changes in beam tension
  - Changes in temperature cause beam expansion/contraction, affecting the measured strain
  - These temperature-induced changes manifest as drift observed in the load range and offset of the dynamometer card
Beam-Mounted Strain Gauge Sources of Error

- Measurement principle incorrectly assumes that polished rod and pitman loads imparts only a bending moment on the beam.

- In fact, there is both a perpendicular, bending force (blue) and parallel force (green) that is compressive or tensile depending on crank angle.

- The parallel load components prevent the measured strain from being strictly analogous to polished rod load.
Beam-Mounted Strain Gauge Summary

- Useful only as a qualitative representation of polished rod load
  - May be acceptable for surface dynamometer-only wellsite control
- Will produce questionable results for all values calculated from surface dynamometer data
  - Downhole dynamometer
  - Gearbox torque
  - Structure loading
  - Rod stress
Polished Rod Load Cell

- Installed on the carrier bar beneath the polished rod clamps, providing direct measurement of polished rod load
- Uses a strain gauge as the base measurement element, but in a full-bridge circuit configuration
  - Output changes linearly with respect to the force applied
- Inherently temperature compensated
  - Changes in temperature cause an equal resistance change in all four gauges
Polished Rod Load Cell Disadvantages

• Polished rod must be clamped off during installation/replacement
• Load cell and cable must be removed/reinstalled during a workover, creating an opportunity for damage to occur
• Cable is susceptible to damage during operation, particularly on Mark II, air balance, and Rotaflex units
Polished Rod Load Cell Zero Offset

- A perfectly balanced strain gauge bridge will provide zero output with no load applied.
- However, manufacturing tolerances of the gauges and strain induced during assembly result in a slight imbalance of the bridge.
- This imbalance causes a small voltage to be output at zero load, referred to as the zero offset.
- Most controllers have a simple procedure to connect the load cell to the RPC with no load and measure the zero offset.
-Skipping this step will cause all points in the surface dynamometer to be shifted up or down by the load value associated with the zero offset.
Polished Rod Load Cell Summary

• Predominant sensor used for polished rod load measurement

• Requires only zero offset correction to provide accurate load readings

• Proportional output, direct measurement, and temperature compensation provide superior results when compared to beam-mounted strain gauges
Modern variable frequency drives (VFD) are capable calculating torque output of the motor in ft-lbs based on current measurement.

If the API geometry of the pumping unit is known, motor torque and crank angle can be used to infer a polished rod load value.

The goal is to provide polished rod load measurement without installing a load sensor and with no load sensor cable to break.
Inferred Polished Rod Load Sources of Error

- Motor must be *tuned* to determine the motor’s **no-load current**
  - No-load current is critical to determining excitation vs. torque-producing current
- Ideally, a rotational motor tune is performed with the motor decoupled from the pumping unit
- More commonly, a non-rotational tune is performed, where no-load current is manually entered or calculated based on measured stator resistance
  - This can lead to errors in the inferred polished rod loads, as no-load current is not directly measured during a non-rotational tune
Inferred Polished Rod Load Sources of Error

- API geometry must be properly configured, or errors in load calculation will occur
  - Required dimensions indicated at right
  - Structural imbalance
  - Effective counterbalance
  - Motor sheave & gearbox ratios
- On units without available catalog data, geometry must be measured in the field
Inferred Polished Rod Load Summary

• Inferring polished rod load from VFD data can eliminate the need for a load sensor and cable.

• Calculations depend on accurate motor tuning and API geometry values.

• Errors in no-load current from motor turning or API geometry will lead to errors in the inferred polished rod load values.
POSITION MEASUREMENT METHODOLOGY
Position Switch

- A reed switch is embedded in a stainless steel wand for ruggedness and ease of installation
- A magnet is attached to the inside of the crank arm or counterweight
- As the magnet passes in front of the wand, the switch closes, giving the rod pump controller a reference position value once per stroke
Position Switch

- The switch closure is used as a reference point, the RPC internally generates the other position points required to plot a dynamometer.

- The RPC must be calibrated to determine the time difference between the switch closure and top of stroke.

- This calibration is used to scale the internally generated position points.
Position Switch Sources of Error

- The RPC typically assumes polished rod movement is sinusoidal, which can cause errors in the calculated position data.

- Errors in the top of stroke calibration will rotate the surface dynamometer, causing the downhole dynamometer to lean left or right.
  - This may give the appearance of tubing movement that is not occurring.
  - Will cause errors in calculation of gearbox torque and inferred production.

- Calibration must be repeated after SPM, stroke length, or counterbalance is changed.
Position Switch Summary

• Simple, low-cost solution for determining polished rod position

• Requires proper top of stroke calibration to produce acceptable dynamometer cards

• Even with proper calibration, will produce lowest quality position measurement of available sensors
Hall-Effect Transducers

- A Hall-effect transducer is a solid-state device with an analog output signal that increases in the presence of a magnetic field
- Similar to a position switch, but better suited for high-speed applications
- Two transducers are used, one to measure crank revolutions and another to measure motor revolutions
Hall-Effect Transducers

- Crank arm transducer provides a reference point once per stroke (bottom or top of stroke)
- Each motor revolution indicates an incremental change in crank angle
- Polished rod position is continuously calculated from crank angle based on API 11E geometry (required dimensions noted at left)
Hall-Effect Transducer
Sources of Error

• API dimensional data must be accurate to properly calculate polished rod position
  – A and C dimensions will vary due to field adjustment available in some units where the walking beam attaches to the saddle bearing, as well as manufacturing tolerances
  – If dimensions are not known, they must be measured in the field (difficult on larger units)

• Phase angle adjustment must be properly set
  – This corrects for the offset between when the crank arm transducer detects the magnet and when the reference point (TOS/BOS) is actually reached
  – If the phase angle adjustment is incorrect the resulting surface and downhole cards will be rotated left or right (similar to a position switch with incorrect TOS)
Hall-Effect Transducer Summary

• Improves upon position switch by providing continuous position calculation using motor revolutions

• Requires proper configuration of API geometry and phase angle adjustment to produce acceptable dynamometer cards
Inclinometer

- Utilizes an accelerometer to measure the angle of the beam as it varies throughout the stroke.
- In a stationary system, an accelerometer detects the direction of pull from the Earth's gravity, i.e., the angle of inclination of the sensor.
- Directly relates changes in beam angle to changes in polished rod position.
Inclinometer Sources of Error

- Proper installation must account for which side of the pumping the sensor is installed on.
- The standard installation on the right side (wellhead to the operator’s right when looking at the unit) will output an increasing voltage as the polished rod is lifted.
Inclinometer Sources of Error

- A sensor installed on the left side will output a decreasing voltage as the polished rod is lifted
  - To account for this, alternate wiring is used to reverse the signal output on the left side
  - Without this compensation, the dynamometer card would be plotted in reverse
Inclinometer Sources of Error

- Early inclinometers used a simple filter to reduce distortions caused by vibration of the pumping unit
  - This filter creates a time delay in the response of the output and causes the card to lean to the left
  - A de-skew adjustment in the RPC is used to correct this, similar to the phase angle adjustment used for the Hall-effect transducer
- Newer microelectromechanical systems (MEMS) based inclinometers more effectively filter the distortions caused by vibration, producing a cleaner signal without requiring skew adjustment in the rod pump controller
Inclinometer Summary

• Provides most direct measurement of polished rod position by measuring the angle of the walking beam

• Care must be taken regarding installation position and wiring to produce the correct output

• Older inclinometers required filtering that may skew the position output and rotate the dynamometer card, this is not necessary on newer MEMS inclinometers
MEASUREMENT ERROR
EXAMPLES
Well A utilizes a beam-mounted strain gauge for measuring polished rod load.

Compared to the orange predicted card, the measured surface card is shifted significantly lower, exhibits a narrower profile, and a portion of the downhole card is below the zero load line.
A – Beam-Mounted Strain Gauge Calibration

Before Load Calibration

After Load Calibration
## A – Beam-Mounted Strain Gauge Calibration

<table>
<thead>
<tr>
<th></th>
<th>Pump-off Card (Uncorrected)</th>
<th>Pump-off Card (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Polished Rod Load (lbs)</td>
<td>25,604</td>
<td>31,099</td>
</tr>
<tr>
<td>Minimum Polished Rod Load (lbs)</td>
<td>10,769</td>
<td>12,637</td>
</tr>
<tr>
<td>Gearbox Torque (in-lbs / %)</td>
<td>558,000 / 87</td>
<td>654,000 / 102</td>
</tr>
<tr>
<td>Structure Loading (%)</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>Peak Rod Stress (%)</td>
<td>93</td>
<td>119</td>
</tr>
</tbody>
</table>
Well B illustrates the potential for signal drift when using a beam-mounted strain gauge.

On day one, a positive load offset is clearly visible.

On day two, with no adjustment of the RPC configuration, the offset appears to disappear.
B – Beam-Mounted Strain Gauge Drift

Day One – Zero Offset Present

Day Two – Load Signal Drifted Down
# B – Beam-Mounted Strain Gauge Drift

<table>
<thead>
<tr>
<th></th>
<th>Day One (Zero Offset)</th>
<th>Day Two (Strain Gauge Drift)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Polished Rod Load (lbs)</td>
<td>34,000</td>
<td>31,400</td>
</tr>
<tr>
<td>Minimum Polished Rod Load (lbs)</td>
<td>14,645</td>
<td>12,206</td>
</tr>
<tr>
<td>Gearbox Torque (in-lbs / %)</td>
<td>880,000 / 96</td>
<td>854,000 / 93</td>
</tr>
<tr>
<td>Structure Loading (%)</td>
<td>93</td>
<td>86</td>
</tr>
<tr>
<td>Peak Rod Stress (%)</td>
<td>60</td>
<td>64</td>
</tr>
</tbody>
</table>
Well C exhibits a positive zero offset with a polished rod load cell.

Downhole cards elevated above zero always indicate a zero offset error.
C – Polished Rod Load Cell
Zero Offset

<table>
<thead>
<tr>
<th>Zero Offset Present</th>
<th>After Zero Offset Correction</th>
</tr>
</thead>
</table>

- Zero Offset Present
- After Zero Offset Correction
## C – Polished Rod Load Cell
Zero Offset

<table>
<thead>
<tr>
<th></th>
<th>Full Card (Uncorrected)</th>
<th>Full Card (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Polished Rod Load (lbs)</td>
<td>19,471</td>
<td>17,308</td>
</tr>
<tr>
<td>Minimum Polished Rod Load (lbs)</td>
<td>7,450</td>
<td>6,268</td>
</tr>
<tr>
<td>Gearbox Torque (in-lbs / %)</td>
<td>494,000 / 77</td>
<td>449,000 / 70</td>
</tr>
<tr>
<td>Structure Loading (%)</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Peak Rod Stress (%)</td>
<td>97</td>
<td>84</td>
</tr>
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</table>
• Well D shows a poor top of stroke calibration for an installation using a position switch
• Some tubing movement is expected (TAC is ~3,000’ above SN depth)
• The downhole card falsely appears to show significant tubing movement and a shorter than normal downhole stroke
D – Position Switch Top of Stroke Error

Full Card Before TOS Calibration

Full Card After TOS Calibration
D – Position Switch Top of Stroke Error

Pump Off Card Before TOS Calibration

Pump Off Card After TOS Calibration
## D – Position Switch Top of Stroke Error

<table>
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<tr>
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<th>Pump-off Card (Uncorrected)</th>
<th>Pump-off Card (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gearbox Torque (in-lbs / %)</strong></td>
<td>181,000 / 56</td>
<td>265,000 / 82</td>
<td>147,000 / 45</td>
<td>175,000 / 54</td>
</tr>
<tr>
<td><strong>Peak Rod Stress (%)</strong></td>
<td>75</td>
<td>69</td>
<td>72</td>
<td>65</td>
</tr>
<tr>
<td><strong>Gross Stroke (in)</strong></td>
<td>89.3</td>
<td>104.1</td>
<td>87.9</td>
<td>103.0</td>
</tr>
<tr>
<td><strong>Net Stroke (in)</strong></td>
<td>62.4</td>
<td>92.6</td>
<td>35.7</td>
<td>52.1</td>
</tr>
<tr>
<td><strong>Net Stroke Displacement (BPD)</strong></td>
<td>68.5</td>
<td>101.8</td>
<td>39.2</td>
<td>57.3</td>
</tr>
</tbody>
</table>
• Well E utilizes Hall-effect transducers for position, but does not have the proper phase angle adjustment configured

• The field card (blue) incorrectly indicate tubing movement compared to the predicted card (orange)
E – Hall-Effect Transducer Phase Angle Error

Full Card Before Phase Angle Adjustment

Full Card After Phase Angle Adjustment
E – Hall-Effect Transducer Phase Angle Error

Pump Off Card Before Phase Angle Adjustment

Pump Off Card After Phase Angle Adjustment
### E – Hall-Effect Transducer Phase Angle Error

<table>
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<tr>
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<th>Pump-off Card (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gearbox Torque</strong></td>
<td>321,000 / 100</td>
<td>305,000 / 95</td>
<td>325,000 / 101</td>
<td>305,000 / 95</td>
</tr>
<tr>
<td><strong>Peak Rod Stress (%)</strong></td>
<td>78</td>
<td>77</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td><strong>Gross Stroke (in)</strong></td>
<td>99.7</td>
<td>104.8</td>
<td>102.1</td>
<td>105.1</td>
</tr>
<tr>
<td><strong>Net Stroke (in / %)</strong></td>
<td>93.5</td>
<td>100.9</td>
<td>93.3</td>
<td>100.1</td>
</tr>
<tr>
<td><strong>Net Stroke Displacement (BPD)</strong></td>
<td>319.4</td>
<td>344.7</td>
<td>323.6</td>
<td>347.0</td>
</tr>
</tbody>
</table>
Well F uses an older inclinometer, filtered to reduce signal noise caused by vibration of the pumping unit. The filtering has caused a time lag of the position signal, evident in the left lean of the downhole dynamometer card.
F – Inclinometer Skewed Position Data

Full Card with Skewed Position Data

Full Card with De-Skewed Position Data
F – Inclinometer Skewed Position Data

Pump Off Card with Skewed Position Data

Pump Off Card with De-Skewed Position Data
## F – Inclinometer Skewed Position Data

<table>
<thead>
<tr>
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<th>Pump-off Card (Uncorrected)</th>
<th>Pump-off Card (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox Torque (in-lbs / %)</td>
<td>419,000 / 65</td>
<td>436,000 / 68</td>
<td>410,000 / 64</td>
<td>471,000 / 73</td>
</tr>
<tr>
<td>Peak Rod Stress (%)</td>
<td>85</td>
<td>85</td>
<td>80</td>
<td>83</td>
</tr>
<tr>
<td>Gross Stroke (in)</td>
<td>151.0</td>
<td>137.0</td>
<td>138.6</td>
<td>132.2</td>
</tr>
<tr>
<td>Net Stroke (in)</td>
<td>145.3</td>
<td>127.6</td>
<td>108.9</td>
<td>103.7</td>
</tr>
<tr>
<td>Net Stroke Displacement (BPD)</td>
<td>472.8</td>
<td>415.3</td>
<td>354.3</td>
<td>337.4</td>
</tr>
</tbody>
</table>
Conclusions

• The dynamometer card is one of the most important tools used for control and analysis of rod pumped wells

• It is important to understand the strengths and weaknesses of the variety of sensors available for measuring dynamometer inputs

• Proper installation, calibration, and RPC configuration is required for each sensor type

• Errors in dynamometer input data can result in poor well control, under- or over-reported inferred production, and possible overloading of the gearbox, pumping unit structure, or sucker rods
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